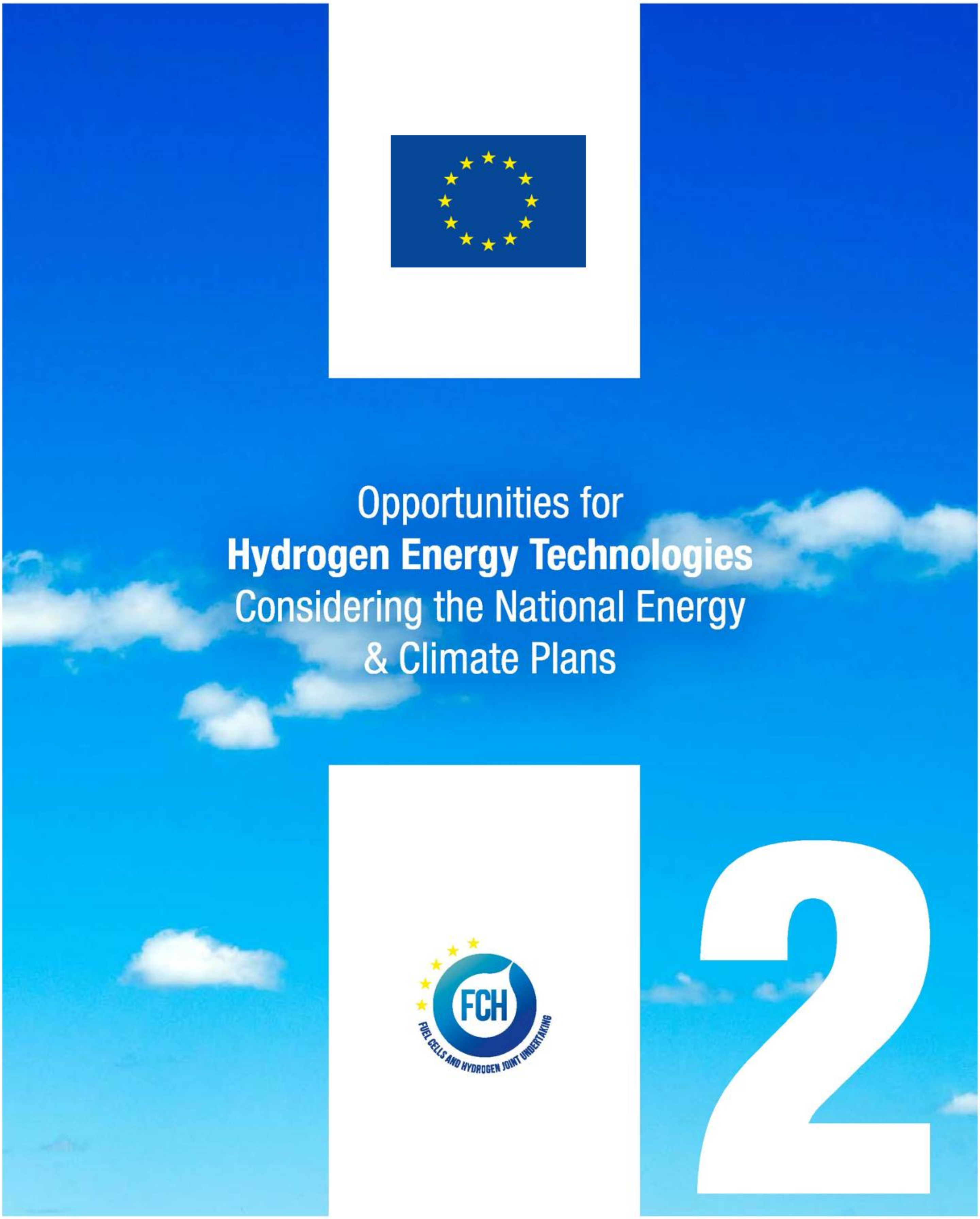

Opportunities for **Hydrogen Energy Technologies** Considering the National Energy & Climate Plans

Contract details

Fuel Cells and Hydrogen 2 Joint Undertaking (FCH 2 JU)

Study on Opportunities arising from the inclusion of Hydrogen Energy Technologies in the National Energy & Climate Plans (Ref. FCH / OP / Contract 234)

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Date

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Disclaimer

The Fuel Cells and Hydrogen Joint Undertaking (FCH JU), in consultation with the European Commission - DG Energy, has commissioned a study on the “Role of Hydrogen in the National Energy and Climate Plans”. This study was conducted by the consultancies Trinomics and LBST and its results are presented in this report.

The information and views set out in this report are those of the authors and do not necessarily reflect the official opinion of the FCH 2 JU. The information is based on the NECPs that were publicly available in April 2020. The FCH 2 JU does not guarantee the accuracy of the data included in this study. Neither the FCH 2 JU nor any person acting on the FCH 2 JU’s behalf may be held responsible for the use which may be made of the information contained therein.

Rotterdam, July 2020

Opportunities for Hydrogen Energy Technologies considering the National Energy & Climate Plans

Final Report

Client: Fuel Cells and Hydrogen 2 Joint Undertaking
Reference number: FCH / OP / Contract 234

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ABSTRACT

This study analyses the role of hydrogen in the National Energy and Climate Plans (NECPs) and identifies and highlights opportunities for hydrogen technologies to contribute to effective and efficient achievement of the 2030 climate and energy targets of the EU and its Member States.

The study focuses on the potential and opportunities of renewable hydrogen, produced by electrolysers using renewable electricity and of low-carbon hydrogen, produced by steam methane reforming combined with CCS. The opportunities for and impacts of hydrogen deployment are assessed and summarised in individual fiches per Member State.

The study analyses to what extent policy measures and industrial initiatives are already being taken to facilitate large-scale implementation of hydrogen in this and the next decades. The study concludes by determining the CO_2 reduction potential beyond what is foreseen in the NECPs through hydrogen energy technologies, estimating the reduction of fossil fuel imports and reliance, the prospective cost, and the value added and jobs created. National teams working on decarbonisation roadmaps and updates of the NECPs are welcome to consider the opportunities and benefits of hydrogen deployment identified in this study.

TEC1216EU

CONTENTS

Executive Summary

Given that renewable and low-carbon hydrogen will be essential to support the decarbonisation of the energy system, it is important to identify and assess the opportunities offered by large-scale deployment of hydrogen in view of possibly integrating them into future updates of the national climate and energy planning and roadmaps towards a low-carbon energy system.

This study aims to analyse the role of renewable and low-carbon hydrogen in the National Energy and Climate Plans (NECPs), and to identify and highlight the opportunities for hydrogen technologies to contribute to effective and efficient achievement of the 2030 climate and energy targets of the EU and its Member States. Next to the information from the NECPs, additional publicly available material and the consultant's proprietary analytical tools were used. The opportunities for and impacts of hydrogen deployment are assessed per Member State and are summarised in individual fiches per Member State. This information should contribute to ensuring that attractive options for using hydrogen technologies are duly considered by the Member States.

This report provides an **analysis of the NECPs** for 2021-2030 submitted by the EU Member States (see Chapter 2). The analysis focuses on the extent to which hydrogen deployment is addressed by the NECPs, and provides an overview of the hydrogen related targets, policies and initiatives covered by the NECPs.

Further, the report includes an **opportunity assessment** regarding the deployment of hydrogen technologies (see Chapter 3). The opportunities identified are mainly based on the technical potentials and existing infrastructure per Member State and reflect the national potential for hydrogen deployment, based on the three pillars of the value chain: production, delivery (transport, distribution and storage), and use/demand. The fourth influencing factor addresses the political and industrial environment in a qualitative way as an enabler for hydrogen deployment.

Finally, the report presents an overview of the **national impacts of deploying renewable hydrogen** (see Chapter 4). This includes estimates of 2030 hydrogen demand in a low and a high scenario in the EU Member States (plus UK) in the sectors industry, built environment, transport and power, and the resulting impact in terms of greenhouse gas emission reductions, infrastructure implications as well as security of energy supply, financial impacts, employment and value added.

As a whole these assessments can support Member States in determining or adapting their hydrogen policies and targets for 2030 and beyond and how to enable hydrogen deployment with the right set of policy measures. National teams working on decarbonisation roadmaps and updates of the NECPs are welcome to consider the opportunities and benefits of hydrogen deployment identified in this study.

The scenario assessment shows substantial potential benefits of hydrogen deployment by 2030. The main assumptions and results are hereafter briefly presented.

Hydrogen demand

Two (high and low) scenarios of hydrogen demand in 2030 (42 and 183 TWh/a respectively for EU28) are developed, based on different levels of ambition linked to the national context in each Member State. The resulting values are presented in Table 0-1 and Table 0-1 .

For most EU Member States, a significant increase of hydrogen demand is assumed in **transport**, especially for passenger cars, buses, trucks and trains, and to a limited extent in aviation (through hydrogen-based liquid fuels or Power to Liquid) and inland navigation. A significant increase of hydrogen demand is also assumed in **industry** (especially in refineries, chemical industry and the iron and steel sector). Some industries use at present fossil-based hydrogen as feedstock or as reducing agent, which could be replaced by renewable hydrogen. Switching high temperature heat processes fuels to renewable hydrogen represents another important potential use considered in the scenarios. In the **building** sector, hydrogen can replace part of the current use of natural gas; it can in the short/medium term be distributed via existing gas grids through admixture to natural gas, and in the long term via dedicated networks. The building sector is expected to have in the low scenario a limited demand of hydrogen by 2030 but would have a stronger demand in the high scenario. The scenarios assume only a marginal share of electricity generation from hydrogen by 2030, coming from combined heat and power installations.

Hydrogen production

To cover the hydrogen demand estimated in the 2 scenarios, 13 and 56 GW respectively of electrolyser capacity will have to be installed, assuming an average annual utilisation rate of 4.800 full load hours. To this end, 68 and 291 TWh/a respectively of renewable power will be needed, based on an electrolysis efficiency of 69%. “Surplus” electricity from the markets in times of low electricity wholesale prices can be used for this purpose as well. However, the main share will have to be covered by dedicated renewable electricity sources. For three countries with a high readiness for CO_2 storage, namely Germany, the Netherlands and the UK, low-carbon hydrogen produced via steam methane reforming (SMR) in combination with CCS is considered as an alternative. Although a combination of electrolysis and SMR production is expected to develop in practice, the study shows that SMR capacity of 2 and 9 GW_{H2} respectively, would be needed to fully replace the electrolysers and cover the corresponding hydrogen demand in these countries (16 and 74 TWh_{H2}/a respectively).

Estimated socio-economic and environmental impacts

The annual costs to produce renewable hydrogen (including the cost of dedicated renewable electricity generation), to develop the transport infrastructure (or adapt the existing one) and end-user applications would in the considered scenarios reach 10 and 33 billion EUR, respectively. The cumulative investments needed up to 2030 would reach 70 and 249 billion EUR, respectively. These activities will generate value added in the domestic economy, amongst others, by creating jobs in manufacturing, construction and operation of hydrogen technologies estimated at 104 000 and 357 000 jobs respectively, and will contribute to greenhouse gas emission reductions. This is particularly important in hard-to-decarbonize energy uses, such as heavy-duty transport, steel production, refining or ammonia and methanol production. According to the European EUCO3232.5 scenario, there is a remaining gap of 1.5 Gt_{CO2}/a in emission reduction plans that needs to be closed in order to achieve 2030 goals. In the scenarios considered, the deployment of hydrogen could contribute 20 and 67 Mt CO_2/a respectively to this goal, which is equivalent to 1.4% and 4.6% respectively of the required emission reduction.

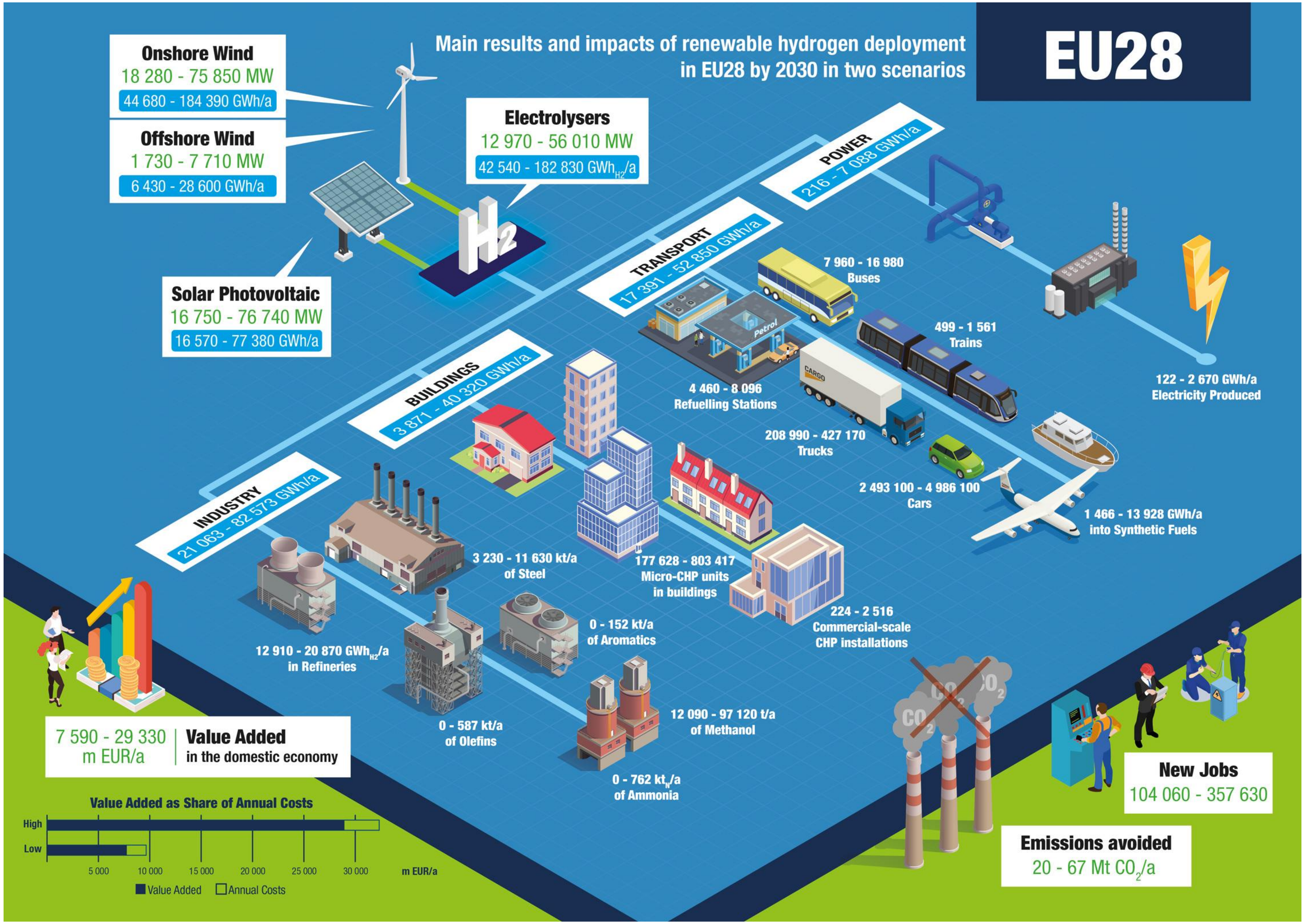
The following table and infographic present the major outcomes from the scenario assessment.

Table 0-1 Main results and impacts of hydrogen deployment by 2030 in the two scenarios modelled in the present study[1]

Member State	Hydrogen demand (TWh_{H2}/a)	Electrolysis capacity in GW_{el} (SMR+CCS capacity in GW_{H2})[2]	Avoided fossil fuel imports (TWh/a)	Value added (million EUR)	Jobs (FTEs)
Austria	2 - 6	0.6 - 2.0	4 - 11	303 - 980	3324 - 10509
Belgium	1 - 7	0.4 - 2.3	2 - 8	224 - 1140	2525 - 10735
Bulgaria	0.8 - 1.4	0.3 - 0.5	1 - 2	109 - 190	3354 - 6001
Croatia	0.1 – 0.4	0.03 - 0.2	0.1 - 1	13 - 70	177 - 591
Cyprus	0.02 - 0.1	0.01 - 0.1	0.03 - 0.1	5 - 30	97 - 599
Czech	0.4 - 2	0.1 - 0.6	1 - 3	77 - 290	535 - 1330
Denmark	0.4 - 2	0.1 - 0.6	1 - 2	66 - 290	558 - 1442
Estonia	0.01 - 0.1	0.005 - 0.05	0.03 - 0.2	2 - 20	70 - 483
Finland	1 - 5	0.3 - 1.1	3 - 11	273 - 900	2728 - 8854
France	4 - 20	1.2 - 5.3	8 - 27	669 - 2680	10379 - 33648
Germany	9 - 41	3.0 - 13.7 (1.1 - 5.0)	19 - 67	1918 - 7620	23192 - 82799
Greece	1 - 3	0.4 - 1.0	2 - 4	229 - 540	4450 - 10432
Hungary	1 - 2	0.3 - 0.9	1 - 3	134 - 360	721 - 1548
Ireland	0.1 - 1	0.0 - 0.3	0.2 - 1	15 - 130	246 - 1797
Italy	4 - 20	1.3 - 6.7	7 - 26	779 - 3510	11509 - 41760
Latvia	0.05 - 0.2	0.02 - 0.1	0.1 - 0.3	8 - 30	316 - 1222
Lithuania	0.1 - 0.7	0.04 - 0.3	0.1 - 1	18 - 120	569 - 3742
Luxembourg	0.1 - 0.4	0.1 - 0.3	0.2 - 1	44 - 160	420 - 1531
Malta	0.01 - 0.05	0.003 - 0.03	0.01 - 0.04	1 - 10	33 - 224
the Netherlands	3 - 12	0.8 - 3.6 (0.3 - 1.5)	4 - 14	460 - 1930	5112 - 18204
Poland	2 - 6	0.7 - 1.7	3 - 8	343 - 870	3597 - 8608
Portugal	1 - 7	0.3 - 2.7	1 - 8	92 - 740	2500 - 18450
Romania	1 - 2	0.3 - 0.8	2 - 3	156 - 350	1925 - 4440
Slovakia	0.4 - 1.1	0.1 - 0.4	1 - 2	59 - 160	1285 - 3609
Slovenia	0.1 - 0.2	0.02 - 0.1	0.1 - 0.3	12 - 30	270 - 686
Spain	4 - 17	1.0 - 4.1	7 - 20	604 - 2360	10527 - 35827
Sweden	2 - 5	0.4 - 1.2	4 - 11	312 - 880	1106 - 2593
UK	4 - 21	1.1 - 5.6 (0.5 - 2.5)	7 - 27	664 - 2940	12532 - 45975
EU28	**42 - 183**	**13 - 56 (1.9 - 8.9)**	**80 - 259**	**7 590 - 29 330**	**104 060 - 357 630**

[1] The values mentioned correspond to the national production and consumption of hydrogen. Trade between EU Member States and imports from non-EU countries are not considered in the scenarios.
[2] Low-carbon hydrogen production via SMR+CCS is considered as an alternative for renewable hydrogen production via electrolysis in countries with high readiness for CO_2 storage, i.e. Germany, the Netherlands and the UK.

Figure 0-1 Main results and impacts of hydrogen deployment for the EU28 by 2030 in the two scenarios modelled in the present study



Résumé exécutif

Étant donné que l'hydrogène renouvelable et bas carbone sera essentiel en vue de soutenir la décarbonation du système énergétique, il est important d'identifier et d'évaluer les opportunités offertes par le déploiement de l'hydrogène à grande échelle et d'envisager son intégration dans les planifications climatique et énergétique nationales et dans les feuilles de route vers un système énergétique bas carbone.

Cette étude vise à analyser le rôle de l'hydrogène renouvelable et bas carbone dans les Plans Nationaux Energie Climat (PNEC), et à identifier et mettre en évidence les opportunités pour les technologies de l'hydrogène visant à contribuer à la réalisation efficace et effective des objectifs climatiques et énergétiques de l'UE et de ses États membres à l'horizon 2030. Outre l'information des PNEC, des données publiquement disponibles ainsi que des informations internes et instruments d'analyse du consultant ont été utilisés. Les opportunités et les impacts du déploiement de l'hydrogène sont évalués pour chaque État membre et résumés dans des fiches individuelles. Ces informations devraient contribuer à assurer que les options attractives d'utilisation des technologies de l'hydrogène sont et seront dûment prises en compte par les États membres.

Ce rapport présente une **analyse des PNEC 2021-2030** soumis par les États membres de l'UE (voir chapitre 2). L'analyse se concentre sur la mesure du déploiement de l'hydrogène tel que prévu dans les PNEC, et fournit un aperçu des objectifs, des politiques et des initiatives liées à l'hydrogène tels que repris dans les PNEC.

En outre, le rapport comprend une **évaluation des opportunités** concernant le déploiement des technologies de l'hydrogène (voir chapitre 3). Les opportunités identifiées reposent principalement sur les potentiels techniques et les infrastructures existantes par État membre et reflètent le potentiel national de déploiement de l'hydrogène, sur base des trois piliers de la chaîne de valeur: la production, la livraison (transport, distribution et stockage) et la demande/utilisation. Le quatrième facteur d'influence aborde l'environnement politique et industriel de manière qualitative en tant que catalyseur du déploiement de l'hydrogène.

Enfin, le rapport présente un aperçu des **impacts nationaux liés au déploiement de l'hydrogène renouvelable** (voir chapitre 4). Cela comprend des estimations de la demande d'hydrogène en 2030 dans un scénario faible et élevé dans chaque État membre de l'UE (plus le Royaume-Uni) pour les secteurs de l'industrie, du bâtiment, du transport et de la production d'électricité, ainsi que l'impact résultant en matière de réduction des émissions de gaz à effet de serre, les implications pour les infrastructures ainsi que la sécurité d'approvisionnement énergétique, les impacts financiers, l'emploi et la valeur ajoutée.
Dans l'ensemble, ces évaluations peuvent aider les États membres à déterminer ou à adapter leurs politiques et objectifs en matière d'hydrogène pour 2030 et au-delà, et à soutenir le déploiement de l'hydrogène par des mesures politiques appropriées. Les équipes nationales travaillant sur les feuilles de route pour la décarbonation et les mises à jour des PNEC sont invitées à examiner les opportunités et les avantages du déploiement de l'hydrogène renouvelable tels qu'identifiés dans cette étude.

L'évaluation des scénarios montre des avantages potentiels substantiels relatifs au déploiement de l'hydrogène d'ici 2030.

Les hypothèses et résultats principaux sont ci-après brièvement présentés.

Demande d'hydrogène

Deux scénarios (haut et bas) de demande d'hydrogène en 2030 sont développés, basés sur différents niveaux d'ambition liés au contexte national de chaque État membre. Les résultats sont résumés dans leTable 0-1 Tableau 0-1. Pour la plupart des États membres de l'UE, une augmentation importante de la demande d'hydrogène est supposée dans le **transport**, en particulier pour les voitures particulières, les bus, les camions et les trains, et dans une moindre mesure dans l'aviation (via les carburants liquides à base d'hydrogène ou Power to Liquid) et la navigation intérieure. Une augmentation significative de la demande en hydrogène est également présumée dans l'**industrie** (notamment dans les raffineries, l'industrie chimique et le secteur sidérurgique). Certaines industries utilisent actuellement l'hydrogène d'origine fossile comme matière première ou agent réducteur, lequel pourrait être remplacé par de l'hydrogène renouvelable. Le passage des combustibles fossiles pour des procédés thermiques à haute température vers de l'hydrogène renouvelable représente une autre utilisation potentielle importante également prise en compte dans les scénarios. Dans le secteur du **bâtiment**, l'hydrogène peut remplacer une partie de l'utilisation actuelle de gaz naturel; il peut être distribué à court / moyen terme via des réseaux de gaz existants en étant mélangé au gaz naturel, et à long terme via des réseaux dédiés. Le secteur du bâtiment devrait avoir, dans le scénario bas, une demande limitée d'hydrogène d'ici 2030, mais aurait une demande plus forte dans le scénario haut. Les scénarios présument qu'une part très limitée de l'électricité sera produite sur base d'hydrogène d'ici 2030, notamment dans des installations combinées de chaleur et d'électricité.

Production d'hydrogène

Pour couvrir la demande d'hydrogène estimée dans les 2 scénarios, 13 et 56 GW de capacité d'électrolyseurs devront respectivement être installés, en supposant un taux d'utilisation annuel moyen de 4.800 heures à pleine charge. A cet effet, 68 et 291 TWh / an d'électricité renouvelable seront respectivement nécessaires, sur la base d'un rendement d'électrolyse de 69%. L'électricité «excédentaire» des marchés en période de faibles prix de gros de l'électricité peut également être utilisée à cette fin. Cependant, la majeure partie devra être couverte par des sources d'électricité renouvelable dédiées. Alternativement, les scénarios supposent que dans trois pays relativement avancés en vue du stockage de CO_2, à savoir l'Allemagne, les Pays-Bas et le Royaume-Uni, de l'hydrogène bas carbone peut être produit via le vaporeformage du méthane (SMR) en combinaison avec le CCS. Une capacité SMR de 2 et 9 GW_{H2} respectivement, seraient nécessaires pour remplacer les électrolyseurs et ainsi couvrir la demande d'hydrogène correspondante dans ces pays (16 et 74 TWh_{H2} / an respectivement).

Impacts socio-économiques et environnementaux estimés

Les coûts annuels de production d'hydrogène renouvelable (y compris le coût de production d'électricité renouvelable dédiée), de développement de l'infrastructure de transport (ou d'adaptation de l'infrastructure existante) et des applications des utilisateurs finaux s'élèveraient respectivement dans les scénarios envisagés à 10 et 33 milliards d'euros. Les investissements cumulés nécessaires jusqu'en 2030 atteindraient respectivement 70 et 249 milliards d'euros. Ces activités généreront de la valeur ajoutée dans l'économie européenne, notamment en créant des emplois dans la fabrication, la construction et l'exploitation des technologies de l'hydrogène, estimés respectivement à 104 000 et 357

000 emplois. Elles contribueront à la réduction des émissions de gaz à effet de serre, ce qui s'avère particulièrement important dans les applications d'énergie difficiles à décarboner, telles que le transport lourd, la production d'acier, le raffinage ou la production d'ammoniac et de méthanol. Selon le scénario européen EUCO3232.5, il reste un écart de 1,5 $GtCO_2$ / an dans les plans de réduction des émissions qui doit être comblé pour atteindre les objectifs de 2030. Dans les scénarios envisagés, le déploiement de l'hydrogène renouvelable pourrait contribuer à cet objectif à concurrence de respectivement 20 et 67 Mt de CO_2, ce qui équivaut à 1,4 et 4,6% de la réduction requise des émissions. Le tableau et l'infographie suivants présentent les principaux résultats de l'évaluation des 2 scénarios.

Tableau 0 1 Principaux résultats et impacts du déploiement de l'hydrogène d'ici 2030 dans les deux scénarios modélisés par la présente étude[3]

Etat membre	Demande d'hydrogène (TWh_{H2}/a)	Electrolyse en GW_{el} (SMR+CCS capacité en GW_{H2})[4]	Importation évitée de combustibles fossiles (TWh/a)	Valeur ajoutée (millions EUR)	Emploi (ETP)
Allemagne	9 - 41	3.0 - 13.7 (1.1 - 5.0)	19 - 67	1918 - 7620	23192 - 82799
Autriche	2 - 6	0.6 - 2.0	4 - 11	303 - 980	3324 - 10509
Belgique	1 - 7	0.4 - 2.3	2 - 8	224 - 1140	2525 - 10735
Bulgarie	0.8 - 1.4	0.3 - 0.5	1 - 2	109 - 190	3354 - 6001
Croatie	0.1 – 0.4	0.03 - 0.2	0.1 - 1	13 - 70	177 - 591
Chypre	0.02 - 0.1	0.01 - 0.1	0.03 - 0.1	5 - 30	97 - 599
Danemark	0.4 - 2	0.1 - 0.6	1 - 2	66 - 290	558 - 1442
Espagne	4 - 17	1.0 - 4.1	7 - 20	604 - 2360	10527 - 35827
Estonie	0.01 - 0.1	0.005 - 0.05	0.03 - 0.2	2 - 20	70 - 483
Finlande	1 - 5	0.3 - 1.1	3 - 11	273 - 900	2728 - 8854
France	4 - 20	1.2 - 5.3	8 - 27	669 - 2680	10379 - 33648
Grèce	1 - 3	0.4 - 1.0	2 - 4	229 - 540	4450 - 10432
Hongrie	1 - 2	0.3 - 0.9	1 - 3	134 - 360	721 - 1548
Irlande	0.1 - 1	0.0 - 0.3	0.2 - 1	15 - 130	246 - 1797
Italie	4 - 20	1.3 - 6.7	7 - 26	779 - 3510	11509 - 41760
Lettonie	0.05 - 0.2	0.02 - 0.1	0.1 - 0.3	8 - 30	316 - 1222
Lituanie	0.1 - 0.7	0.04 - 0.3	0.1 - 1	18 - 120	569 - 3742
Luxembourg	0.1 - 0.4	0.1 - 0.3	0.2 - 1	44 - 160	420 - 1531
Malte	0.01 - 0.05	0.003 - 0.03	0.01 - 0.04	1 - 10	33 - 224
Pays-Bas	3 - 12	0.8 - 3.6 (0.3 - 1.5)	4 - 14	460 - 1930	5112 - 18204
Pologne	2 - 6	0.7 - 1.7	3 - 8	343 - 870	3597 - 8608
Portugal	1 - 7	0.3 - 2.7	1 - 8	92 - 740	2500 - 18450
Roumanie	1 - 2	0.3 - 0.8	2 - 3	156 - 350	1925 - 4440
Royaume-Uni	4 - 21	1.1 - 5.6 (0.5 - 2.5)	7 - 27	664 - 2940	12532 - 45975
Slovaquie	0.4 - 1.1	0.1 - 0.4	1 - 2	59 - 160	1285 - 3609
Slovénie	0.1 - 0.2	0.02 - 0.1	0.1 - 0.3	12 - 30	270 - 686

[3] Les valeurs reflètent la production et consommation nationales d'hydrogène. Le commerce entre les États membres de l'UE et les importations en provenance de pays tiers ne sont pas pris en compte dans les scénarios.

[4] La production d'hydrogène bas carbone via SMR + CCS est considerée comme alternative pour la production d'hydrogène renouvelable dans des pays avancés en vue du stockage de CO_2, à savoir l'Allemagne, les Pays-Bas et le Royaume-Uni.

Suède	2 - 5	0.4 - 1.2	4 - 11	312 - 880	1106 - 2593
Tchéquie	0.4 - 2	0.1 - 0.6	1 - 3	77 - 290	535 - 1330
EU28	**42 - 183**	**13 - 56 (1.9 - 8.9)**	**80 - 259**	**7 590 - 29 330**	**104 060 - 357 630**

Definitions and abbreviations

CCS	Carbon capture and storage
CCU	Carbon capture and utilisation
CCUS	Carbon capture, utilisation and storage
CHP	Combined heat and power
CO	Carbon monoxide
CO_2	Carbon dioxide
DRI	Direct reduced iron
DSO	Distribution system operator
EC	European Commission
ENTSOG	European Network of Transmission System Operators for Gas
ETP	Equivalent Temps Plein
ETS	Emissions Trading System
ETR	Energy Transition Related
EU	European Union
EUCO3232.5	Policy scenario reflecting the 32% renewable energy and 32.5% energy savings targets and their impact on the EU energy system
FCH JU	Fuel cells and Hydrogen Joint Undertaking
FTE	Full-time equivalent
GHG	Greenhouse gases
H_2	Hydrogen
IGCC	Integrated gasification combined cycle
IPCEI	Important Projects of Common European Interest
LNG	Liquefied natural gas
Low-carbon hydrogen	Hydrogen produced by steam methane reforming (SMR) combined with CC(U)S
MS	Member State
NECP	National energy and climate plan
OGE	Open Grid Europe
P2X	Power to product
PtL	Power to liquid
PV	Photovoltaic
Renewable hydrogen	Hydrogen produced by electrolysers using renewable electricity
R&D	Research and development
RD&I	Research, development and innovation
R&I	Research and innovation
SET Plan	Strategic Energy Technology Plan
SME	Small and medium enterprises
SMR	Steam Methane Reforming
TEN-E	Trans-European Energy Networks
TSO	Transmission system operator
TYNDP	Ten-year network development plan

1 Context

1.1 Introduction

1.1.1 Objective and scope of the study

According to the EU's long-term vision for a climate neutral economy[5], the role of renewable and low-carbon hydrogen will become essential to effectively and efficiently decarbonise the energy system. It is hence important to timely identify and acknowledge the opportunities offered by the large-scale deployment of hydrogen, and to properly consider its deployment potential. To pick up existing opportunities and prepare the medium- and long-term framework, it is deemed appropriate to duly integrate hydrogen into national climate and energy plans and roadmaps towards a low-carbon energy system.

This study aims to analyse the role of hydrogen in the NECPs for 2021-2030, and to identify and highlight the opportunities for hydrogen technologies to contribute to effective and efficient achievement of the 2030 climate and energy targets of the EU and its Member States. The approach for reaching the 2030 targets has been developed and documented in the NECPs, which determine the pathways chosen by the Member States. If the EU wants to capture the full socio-economic, environmental and energy system benefits of deploying hydrogen technologies, it is important that the opportunities of hydrogen deployment are properly considered by all Member States. Hence, the overarching objective of this study is to *"identify opportunities in terms of jobs, growth, environmental sustainability and energy security through the inclusion of hydrogen energy technologies in the NECPs"*. The opportunities for and impacts of hydrogen deployment are assessed per Member State and are summarised in individual fiches per Member State. This study does not aim to replace NECPs or national roadmaps but can contribute to ensuring that attractive options for using hydrogen technologies are duly considered by the Member States.

The study covers all EU Member States (plus the UK) and focuses on the period up to 2030 (i.e. the period of time covered by the NECPs). While there are major opportunities for hydrogen already up to 2030, the large-scale deployment of renewable and low-carbon hydrogen is expected to mainly take off as of 2030. The study hence assesses to what extent policy measures and industrial initiatives are already being taken to facilitate the large-scale implementation of hydrogen in this and the next decades. Finally, the study focuses on the potential and opportunities of renewable hydrogen, produced by electrolysers using renewable electricity and of low-carbon hydrogen, produced by steam methane reforming (SMR) combined with CC(U)S. In this analysis, national demand is assumed to be covered by national production; cross-border trade between Member States and imports from non-EU countries are hence not considered. Grey hydrogen (hydrogen produced by steam methane reforming without CC(U)S) is also not considered, as its future deployment would not be compliant with the 2030 and 2050 policies and objectives.

The study concludes by determining the CO_2 reduction potential beyond what is foreseen in the NECPs through hydrogen energy technologies, estimating the cost involved and jobs created. National teams working on decarbonisation roadmaps and updates of the NECPs are welcome to consider the additional

[5] European Commission (2018a). COM/2018/773, A clean planet for all. A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy

CO_2 reductions and the opportunities and economic benefits of hydrogen deployments identified in this study.

1.1.2 Structure of the report

Chapter 1 (this chapter), provides an **introduction** to this assignment, as well as the **methodology used for the opportunity and scenario assessment.**

Chapter 2 provides an **analysis of the final NECPs** for 2021-2030 that were available in April 2020 and of the draft NECPs for the other Member States. The analysis focuses on the extent to which hydrogen deployment is addressed by the NECPs, and a detailed overview of the hydrogen related targets, policies and initiatives covered by the NECPs.

Chapter 3 provides the results of the **opportunity assessment** based on four influencing factors. The opportunities identified are mainly based on the technical potentials and existing infrastructure in each Member State and reflect the national potential for hydrogen, based on the three pillars of the value chain: production, delivery (transport, distribution and storage), and demand. The fourth influencing factor addresses the political and industrial environment in a qualitative way as an enabler for hydrogen deployment.

Chapter 4 provides an overview of the **national impacts of deploying hydrogen**. This includes estimates of 2030 hydrogen demand in a low and a high scenario in the EU Member States (plus UK) in the sectors industry, built environment, transport and power, the resulting environmental impact in terms of greenhouse gas emission reductions, infrastructure implications as well as security of energy supply, financial impacts, employment and value added.

As a whole these assessments can support Member States in determining or adapting their hydrogen policies and targets for 2030 and beyond and how to support hydrogen deployment with the right set of policy measures.

Chapter 5 presents the **conclusions and recommendations.**

In addition, the report includes the following annexes:

- Annex A – Detailed methodology, assumptions and sources;
- Annex B - Hydrogen energy technologies information;
- Annex C - Assumptions for socio-economic assessment at sector level;
- Annex D - Reference data for Scenario Assessment per Member State;
- Annex E - Scenario assessment – Hydrogen demand related inputs and results.

1.2 Methodology

This section provides a brief overview on the methodology used in this study. More details and the assumptions used to estimate the impacts of hydrogen deployment are presented in the annexes.

1.2.1 Methodology used for the analysis of the NECPs

The NECPs and other relevant national documents are reviewed in order to identify main references to hydrogen and PtX, potential sources of hydrogen, targeted use sectors, the role of hydrogen in the energy system and the political ambition to deploy hydrogen generation, delivery and end-use applications. The review also addresses any national hydrogen related objectives mentioned either in the NECP or in a specific national hydrogen roadmap or strategy. The expected national hydrogen consumption in 2030 (where available in the NECP) is compared to the technical potential and the outcome of the two scenarios considered in this study.

1.2.2 Assessment per EU Member State of opportunities for hydrogen deployment

The opportunity assessment per EU Member State encompasses:

- Technical potential for domestic renewable and low-carbon hydrogen production and its potential contribution for providing flexibility to the energy system;
- Existing methane transport, distribution and storage infrastructure and its potential use for hydrogen;
- Current and potential hydrogen demand in the different end-use sectors; and
- Enabling national environment, or drivers that can trigger hydrogen development.

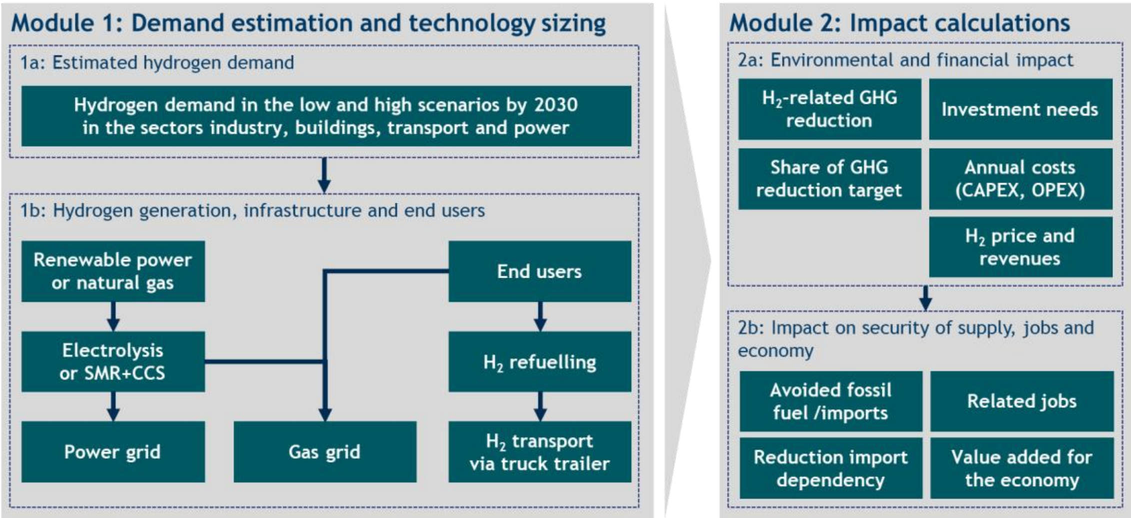
Each of these aspects has been assessed qualitatively using a selection of indicators (see table in annex A). The indicators are used as the basis of the analysis of the opportunities for deploying renewable and low-carbon hydrogen technologies in the different Member States (see results presented in chapter 3).

1.2.3 Scenario assessment per EU Member State of hydrogen deployment

The scenario assessment aims to estimate the impacts of hydrogen technology deployment on the national energy system, economy and GHG emissions in each of the EU Member States. In order to address uncertainty, **two scenarios** are defined with a **low and high share of hydrogen demand** in industry (refining, steelmaking and chemical industry including ammonia, methanol and olefins/aromatics production), heating & cooling in the built environment, transport (passenger cars, buses, trucks, trains, aviation and inland navigation) and electricity generation. The “Low” scenario assumes a limited penetration of hydrogen in the different end-use application; while the “High” scenario assumes that hydrogen development will be strongly supported by increasing competitiveness of hydrogen technologies and enabling policy measures. More details on these scenarios can be found in Annex E.

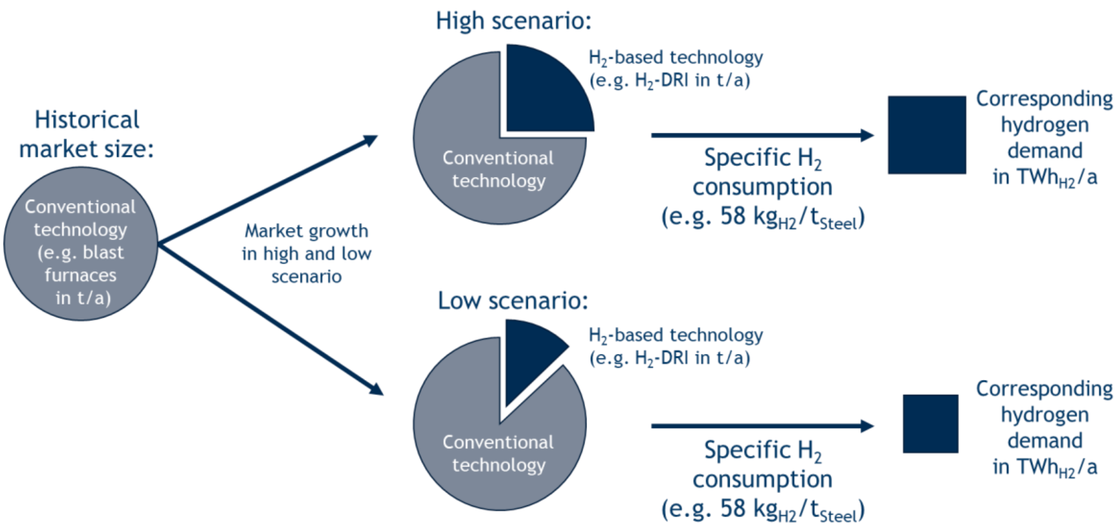
The analysis employs a proprietary input-output calculation model which can be subdivided into two major modules and related sub-modules (see Figure 1-1). In the first step (Module 1), the hydrogen demand is estimated in different sectors and sub-sectors as a starting point of the analysis (Sub-module 1a) and these results are used for the sizing of the corresponding hydrogen-related technologies for generation (for electrolysis in all EU28 and for SMR+CCS in the 3 concerned countries), infrastructures and end-users such as electrolysis, gas grids or end user applications (Sub-module 1b). In the second step (Module 2), the outcomes from the first module are used to assess the corresponding environmental and financial impacts (Sub-module 2a) as well as the impacts on security of energy supply, employment and value added (Sub-module 2b) in each EU Member State.

Figure 1-1 Structure of the input-output model employed in the scenario assessment



Based on the bottom-up approach, the calculation model for the hydrogen demand in each Member State (Sub-module 1a) includes three major input parameter sets (see). First, the size and volume indicators related to the development of the overall demand in the respective sectors and sub-sectors, such as production volumes (e.g. crude steel production in tonnes per year), vehicle usage (e.g. number of person-kilometres driven per year), or the annual energy consumption. The second set of parameters is related to the technology split specifying the share of hydrogen technology in certain volume indicators. This corresponds to the penetration rate of hydrogen in the given market segment. These parameters are derived from techno-economic assessments in available literature for the EU as a whole for the timeframe until 2030 and generally considered as cost-effective on the basis of the literature sources.

Figure 1-2 Approach for estimation of hydrogen demand



At present, some industrial sectors such as ammonia production or refining processes, already use conventional hydrogen from fossil fuels e.g. through steam methane reforming (SMR) or as a by-product from other chemical processes. In this case the penetration rate also corresponds to renewable hydrogen[6] or alternatively in the countries with local carbon storage potential (Germany, the Netherlands and the UK), to low-carbon[7] hydrogen.

Finally, the estimated hydrogen demand in 2030 in each sector and subsector is for each Member State calculated based on the previous results and technology specific energy consumptions and efficiencies. In this way, the Sub-module provides annual demand levels for renewable (or in selected Member States low-carbon) hydrogen in TWh_{H2}/a based on lower heating value. Both scenarios assume that in 2030 renewable or low-carbon hydrogen will be provided to partially substitute current conventional hydrogen production and to cover additional demand (e.g. from the transport sector).

The bottom-up approach of the hydrogen demand calculation provides input data for the assessment of the technology and infrastructure implications per Member State (Sub-module 1b). The assessment includes calculations of the need for dedicated renewable power generation (and in some Member States alternatively for natural gas based SMR capacity) by taking respective efficiencies into account as well as the sizing of the electrolysis (or alternatively of SMR with CCS) based on typical utilisation rates. Moreover, the analysis estimates the number of end-user units in each sector and sub-sector such as the number of FCEVs or hydrogen-powered CHPs as well as corresponding requirements on the power, gas and refuelling infrastructures (including H_2 transport via truck trailers to the refuelling stations).

Environmental and financial impacts (Sub-module 2a) are calculated based on the estimated hydrogen demand and expected size of the hydrogen technology deployment along the entire value chain (i.e. hydrogen generation as well as corresponding infrastructures and end users) from Module 1. It includes H_2-related GHG emission reduction and corresponding share in the national GHG emission reduction target, investment needs and annual costs for the required hydrogen technologies and infrastructures as well as H_2 cost and revenues.

The impact of hydrogen deployment on security of energy supply (Sub-module 2b) is assessed quantitatively based on avoided fossil fuel consumption and imports which can be directly derived from the calculations. The corresponding reduction in import dependency in %-points is then computed by comparing the specific import dependencies, typically expressed on percentage-basis as the share of imported energy in total energy demand, between the cases with and without national hydrogen production and consumption.

The effects on value added and employment are assessed using supply chain analysis of hydrogen technologies. The impacts on the national economy resulting from capital expenditure and operation & management are estimated for every Member State using input-output tables. The value added is defined as the sum of labour costs, taxes and profits. The effects on employment are derived from labour costs of investment in and operation of hydrogen technologies and are quantified as a full-time employment equivalent.

[6] Renewable hydrogen corresponds to hydrogen produced via electrolysis based on fully renewable power generation such as wind energy or PV.
[7] Low-carbon hydrogen corresponds to hydrogen produced via steam methane reforming (SMR) combined with carbon capture and storage (CCS).

1.3 Hydrogen is a key option in the long-term decarbonisation strategy

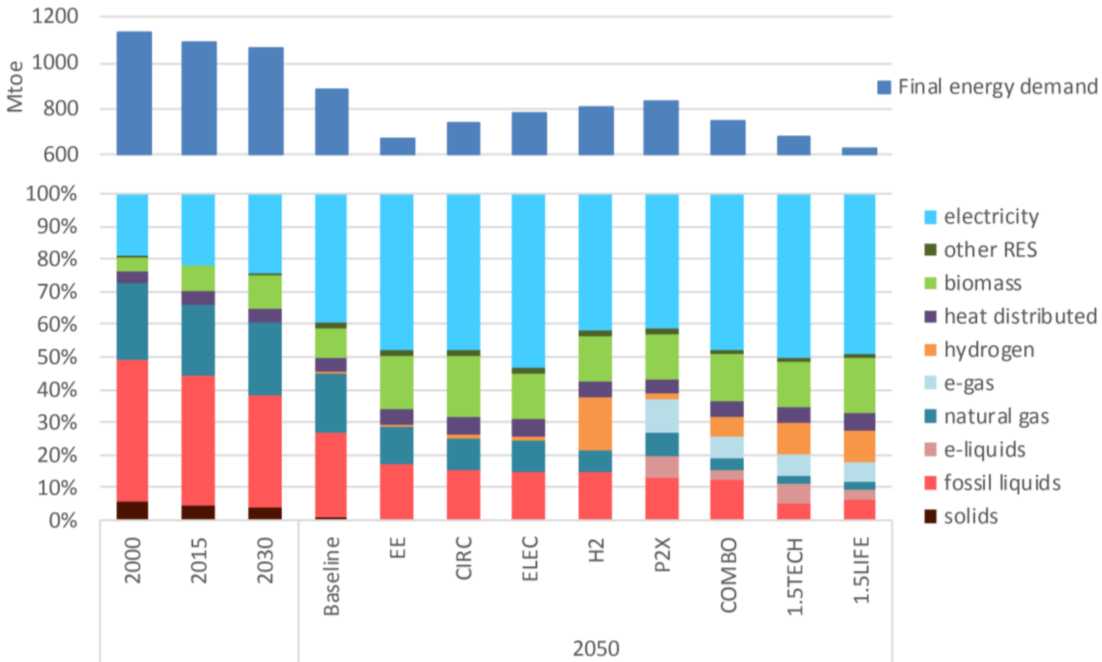
The European Union has agreed on the long-term climate target of reducing its greenhouse gas emissions by 80-95% by 2050. In December 2019, the European Commission unveiled a European Green Deal aimed at putting the European Union on track to reach net-zero global warming emissions by 2050. This Green Deal demonstrates the ambitions of the Commission in climate protection and includes a roadmap of key legislative actions over the coming two years.

Hydrogen and its infrastructure are covered in the Commission communication on the Green Deal under:

The transition to climate neutrality also requires smart infrastructure. Increased cross-border and regional cooperation will help achieve the benefits of the clean energy transition at affordable prices to the citizen. The regulatory framework for energy infrastructure, including the TEN-E Regulation, will need to be reviewed to ensure consistency with the climate neutrality objective. This framework should foster the deployment of innovative technologies and infrastructure, such as smart grids, hydrogen networks or carbon capture, storage and utilisation, energy storage, also enabling sector integration. Some existing infrastructure and assets will require upgrading to remain fit for purpose and climate resilient.[8]

According to the European Commission Long-Term Strategic Vision[9], hydrogen would cover 10% of final energy consumption in 2050 in the 1.5-degree scenarios 1.5TECH and 1.5LIFE, and some 17% in the 2-degree H_2 scenario; in other scenarios, hydrogen has a smaller but still relevant role (see graph below).

Figure 1-3 Share of energy carriers in final energy consumption in the Long-Term Strategy

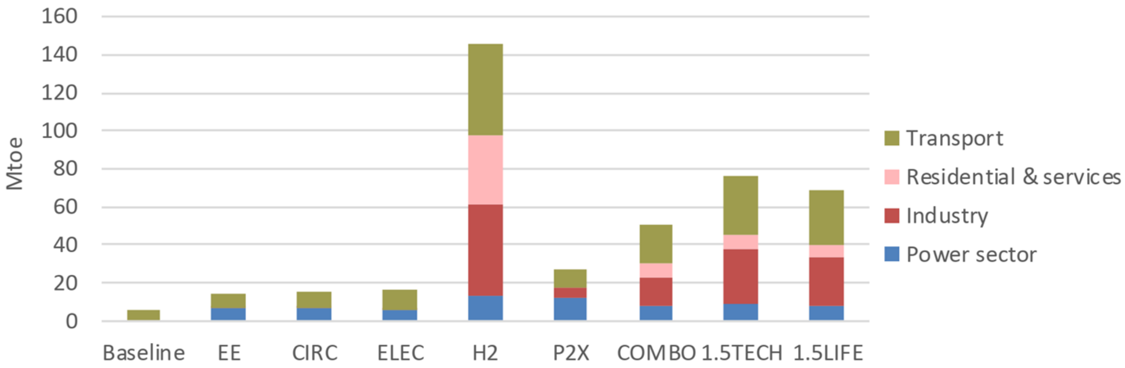


[8] European Commission (2019), COM/2019/640. The European Green Deal

[9] European Commission (2018b), In-depth analysis in support of the Commission communications COM(2018) 773: A Clean Planet for all - A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy

In the Long-Term Strategy scenarios with the highest share of hydrogen, transport and industry are the most important hydrogen consumers. The hydrogen use of the residential and services sector is more limited, except in the H_2 scenario, where it is approximately equivalent to the previous two sectors, and in the P2X scenario, where hydrogen use in the power sector as a flexibility provider is significant (compared to the other sectors' use).

Figure 1-4 Consumption of hydrogen by sector in 2050 in the Long-Term Strategy



1.4 Status-quo regarding existing and planned hydrogen transport infrastructure

In the EU countries where grey hydrogen is at present produced and used in large quantities by a limited number of companies, dedicated pipeline infrastructure exists. The following table shows the hydrogen pipelines in operation in Europe, some of them since many decades.

Table 1-1 Hydrogen pipelines in operation in Europe

Network	Country	Length (km)	Operator
North Europe	Belgium, The Netherlands	949	Air Liquide
Ruhrgebiet	Germany	240	Air Liquide
Rotterdam	The Netherlands	140	Air Products
Leuna-Bitterfeld	Germany	135	Linde
France Center East	France	57	Air Liquide
Rozenburg	The Netherlands	50	Air Products
France South East	France	42	Air Liquide
France East	France	37	Air Liquide
Teesside	UK	35	Linde
Heide	Germany	30	
Stenungsund	Sweden	18	
Dunkerque	France	14	Air Liquide
Hoek-Sluiskil	The Netherlands	12	
Burghausen	Germany	8	
Priolo	Italy	6	Air Liquide
Teesside	UK	5	Air Products
Le Havre	France	4	Air Liquide
Monthey	Switzerland	2	Air Liquide
Porto Marghera	Italy	2	Air Products
Total		***1 786***	

The 12km Hoek-Sluiskil pipeline in the Netherlands was commissioned in 2018. It is a refurbished natural gas pipeline, which is now being used for transporting 4 TWh of hydrogen per year.[10] The other pipelines included in the table have been purpose-built for hydrogen.

A number of other initiatives have emerged in Europe to assess converting natural gas pipelines to hydrogen operation, in view of establishing dedicated hydrogen networks. An early concept, developed to the point of a business case but not yet implemented, is linked to the existing hydrogen pipeline in Heide, northern Germany.[11] More recently, German gas TSO Open Grid Europe (OGE) together with Equinor have announced their joint "H2morrow" project for establishing low-carbon hydrogen at large scale in Germany. Existing methane pipelines would be used to transport by 2030 annually 8.36 of TWh hydrogen produced through steam reforming of natural gas with CCS from Norway to the industry and other end users in North Rhine-Westphalia.[12]

Another German initiative, GET H_2, aims at establishing "the core for a nationwide hydrogen infrastructure in order to make an efficient implementation of the energy transition possible"[13]. Concrete courses, which mainly work with existing infrastructures, are being planned. Partners in this initiative include, among others, the German gas TSOs Gascade, Nowega and Thyssengas. IKEM, a research partner in GET H_2, has carried out a first legal study on regulatory issues related to a hydrogen gas grid based on the German situation.[14]

In the UK, in July 2016, the H21 Leeds City Gate project was launched. The feasibility study confirmed that conversion of the UK gas distribution network to 100% hydrogen would be technically possible and could be delivered at an affordable cost. H21 continues and has recently been awarded a further £6.8 million in Ofgem innovation funding to support a second phase of research and development. This second project stage was planned to begin in 2020 and involves simulating network operations on a specially constructed network. Additionally, network research trials on an unoccupied test site will be undertaken, to demonstrate operational and maintenance procedures – an essential prerequisite to live trials.

In the Netherlands, the network operator association Netbeheer Nederland has commissioned a study on future-proof gas distribution networks including hydrogen networks.[15] The focus of this study is on technical and economic issues. In France, the gas infrastructure operators have in November 2019 published the conclusions of a joint study on the potential role of methane networks, storage facilities and terminals in the hydrogen deployment in France. The study concluded that the technical adaptation costs to integrate large hydrogen volumes into the gas mix would be limited.[16]

The Dutch gas TSO Gasunie is studying the development of a hydrogen gas infrastructure connecting the Netherlands and Germany (Hamburg and Ruhrgebiet) using the methane infrastructure already in place[17]. Gasunie anticipates that hydrogen will be produced from natural gas with CCUS in the short-

[10] https://www.smartdeltaresources.com/en/news/gasunie-hydrogen-pipeline-from-dow-to-yara-now-in-use
[11] EY, LBST, BBH (2013). Roadmap for the Realisation of a Wind Hydrogen Economy in the Lower Elbe Region
[12] Open Grid Europe (2019). H2morrow
[13] https://www.get-h2.de/en/initiativeandvision/
[14] IKEM (2019). Rechtsrahmen für ein H_2 – Teilnetz – Nukleus einer bundesweiten, öffentlichen Wasserstoffinfrastruktur
[15] Kiwa Technology (2018). Toekomstbestendige gasdistributienetten; study commissioned by Netbeheer Nederland
[16] https://www.storengy.com/en/medias/news/gas-infrastructure-and-hydrogen
[17] https://www.gasunie.nl/en/energy-transition/hydrogen

term, while hydrogen from renewable electricity sources such as wind and solar energy will play a substantial role in the energy transition. Gasunie is involved in a number of hydrogen projects including the above-mentioned Hoek-Sluiskil pipeline.

Next to refurbishing existing methane transport infrastructure in view of its use for 100% hydrogen, blending hydrogen with natural gas in existing methane infrastructure is also considered in several Member States. Marcogaz[18] has in 2019 assessed the potential use of methane infrastructure for hydrogen admixture and concluded that:

- major elements of the gas transmission, storage and distribution infrastructure and residential gas appliances are expected to be able to accept 10 vol.-% H_2 without modification;
- some networks and residential appliances are already being operated with 20 vol.-% H_2;
- major elements of the infrastructure and residential appliances are expected to be able to accept 20 vol.-% H_2 with modification;
- many industrial processes (except gas use as feedstock) are expected to be able to accept 5 vol.-% H_2 without modification;
- current power plant gas turbines, industries using natural gas as feedstock and also CNG steel tanks are sensitive to even small quantities of hydrogen and need further R&D/mitigation measures when planning to convey higher hydrogen concentrations;
- thermoprocessing equipment (such as furnaces and burners) are expected to be able to accept 15 vol.-% H_2 with modifications.

[18] Marcogaz (2019), Overview of available test results and regulatory limits for hydrogen admission into existing natural gas infrastructure and end-use appliances

2 Hydrogen in the NECPs

2.1 Deployment of renewable and/or low-carbon hydrogen is to a different extent addressed in the NECPs

The next section is based on the analysis of the final NECPs for 2021-2030 that were available in April 2020. For the countries (France, Germany, Ireland, Romania and the United Kingdom) for whom that final NECP was not available at that moment, the analysis is based on their draft version.

Box 2-1 National Energy and Climate Plans

National Energy and Climate Plans (NECPs) are the new framework set by the European institutions for EU Member States to plan, in an integrated manner, their climate and energy objectives, targets, policies and measures. This new instrument has been introduced by Regulation (EU) 2018/1999 of the European Parliament and of the Council of 11 December 2018 on the Governance of the Energy Union and Climate Action, which consolidates the planning, monitoring and reporting obligations that Member States have under the different pieces of EU legislation across energy, climate and other Energy Union related policy areas.

The NECPs outline how EU Member States intend to address energy efficiency, renewable energy sources, greenhouse gas emissions reductions, interconnections, research and innovation. This approach requires a coordination of purpose across all government departments. It also provides a level of planning that should ease public and private investment. The fact that all EU Member States are using a similar template facilitates cross-border cooperation and coordination and should allow to obtain efficiency gains across borders.

The submitted NECPs cover the time period 2021 to 2030 and will be updated in 2025. These plans are meant to ensure that the EU's 2030 energy and climate targets are met.

Renewable and/or low-carbon hydrogen are mentioned in almost all NECPs; only the Finnish NECP does not explicitly refer to hydrogen, and also the Cypriot NECP does not address hydrogen ('due to lack of data'). Most EU Member States explicitly recognize in their NECP the importance of deploying hydrogen, at least in the long term, referring to its potential contribution to reaching the energy and climate objectives and its potential use in different applications (e.g. Slovenia: "*Hydrogen can play a role in integrating the production of renewable electricity, strengthening security of gas supply and contributing to reach the decarbonisation targets*"). Several NECPs explicitly refer to general political intentions or commitments (e.g. "*Austria foresees to act on promoting investments, exempting taxation and addressing the legal framework for renewable gases*").

Only half of the NECPs mention concrete hydrogen related objectives, either for domestic generation of low carbon/renewable hydrogen (AT, DE, HU, NL), for its end-use in the transport sector (BE, HR, CZ, DE, FR, HU, IT, PT, SK, SL), or in the industry (FR). Denmark, Finland[19] (e.g. steel company SSAB announcing the first zero-carbon steel production by 2026) and Sweden consider hydrogen deployment from a technology and energy vector neutral perspective, and have fixed ambitious global decarbonisation targets (e.g. carbon neutrality by 2035 in Finland), that will pull the uptake of competitive low carbon technologies and applications, among which hydrogen. Despite their technology neutral approach, without a specific agenda for hydrogen, these three Nordic Member States, like many

[19] Finland does not address hydrogen in its NECP, but in the National Energy and Climate Strategy

other Member States, recognise the high interest of hydrogen in the decarbonisation strategy and strongly support R&I activities and innovation through demonstration and pilot projects.

2.1.1 Role of hydrogen in the energy transition

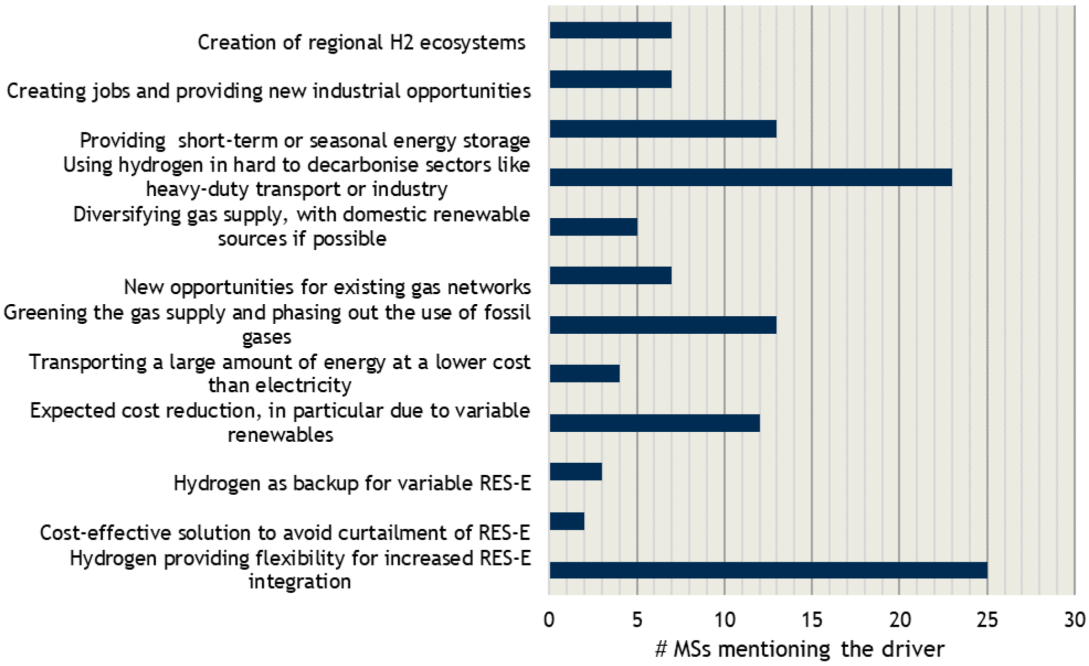
According to the NECPs, many EU Member States (e.g. CY, EL, HR, FR, IE, IT, LT, MT, ES, UK) consider hydrogen applications as a medium or long-term option, that still requires substantial further efficiency improvements (in particular for electrolysers), total cost of ownership reduction and material improvements through dedicated research and innovation activities. Some Member States consider the time period covered by the NECPs (2021-2030) as a preparatory phase, during which focus should be on further fundamental R&D supported by public funding, realisation of innovative and demonstration projects also co-funded by public means, measures to address regulatory barriers and progressive deployment of the required transport and supply infrastructure.

Globally, NECPs recognise hydrogen as a versatile energy carrier and address its value chain considering that its applications are at different maturity levels (e.g. several NECPs mention concrete plans to use fuel cell buses in public transport fleets, while using hydrogen for vessels is still at an early stage and requires more R&I). However, only a minority of Member States consider in their low carbon roadmaps the integration of hydrogen in the whole value chain covering generation, storage, transport and distribution, supply and end-use. Such integration remains complex due to the links across the whole energy supply chain and the different end-use systems (including the industrial, building and transport sectors).

2.1.2 Drivers for and benefits from hydrogen deployment referred to in the NECPs

Figure 2-1 illustrates the drivers mentioned by Member States for considering hydrogen in their NECP and the benefits that they are expecting from deploying hydrogen. The two main drivers/benefits mentioned in almost all NECPs are the contribution of hydrogen to facilitate the increasing share of variable renewable electricity in the energy system, and its potential contribution to reducing GHG emissions in hard to decarbonise market segments, such as heavy duty transport and industry.

Figure 2-1 Main drivers for or expected benefits from deploying hydrogen referred to in the NECPs



Spain refers in its NECP to a specific risk related to producing large volumes of renewable hydrogen through water electrolysis, given its exposure to water scarcity, or even drought (which is already an important concern in Spain as a consequence of climate change).

2.1.3 General approach of hydrogen integration in the NECPs

As the NECPs are structured according to the sections defined in article 3 of Regulation (EU) 2018/1999, the information regarding policies and measures that are directly or indirectly related to hydrogen, is not regrouped in one single section. Only some NECPs comprise very concrete dedicated measures to facilitate hydrogen deployment and its integration into the energy system. Several Member States mention in general their intention to improve the regulatory framework for renewable gas or to implement financial measures to pave the way for renewable gas, including hydrogen. However, the majority of NECPs do not address how the national regulatory frameworks will actually be improved and pay limited attention to concrete measures to effectively address the barriers to hydrogen deployment.

Some 'frontrunning' Member States (e.g. AT, DK, FI, FR, DE, NL, SE, UK) enter the phase of first industrial deployment and strongly focus on the realisation of demonstration and pilot projects, while also addressing regulatory barriers (e.g. determining the threshold and specifications for hydrogen injection into natural gas grids), to start developing dedicated hydrogen infrastructure or adapting existing methane infrastructure, and to improve cost efficiency, in particular of electrolysers, to steer market uptake.

Some Member States (e.g. PL, DE, UK, IE) are specifically considering the potential benefits of hydrogen deployment for their industry at the supply side, which has either a leading position in this field or is strongly interested to accompany the gradual replacement of fossil energy by decarbonised fuels, by deploying a renewable hydrogen economy (e.g. creating new jobs across the whole value chain in the frame of the EU coal region transition).

Box 2-2 Hydrogen as a solution for coal regions in transition

Given the ambitious climate and energy targets, the use of coal is declining in the EU leading to mines closing down in a number of regions across Europe. In this context, the European Commission has launched the 'Platform for Coal Regions in Transition' in 2017 (as part of the coal and carbon-intensive regions in transition initiative included as a non-legislative element of the 'Clean energy for all Europeans' package). The platform "promotes knowledge sharing and exchanges of experiences between EU coal regions, and represents a unique bottom-up approach to a just transition, enabling regions to identify and respond to their unique contexts and opportunities".[20] At present, 18 coal regions from different Member States (Poland, Czechia, Germany, Greece, Romania, Slovakia, Slovenia and Spain) are actively participating in the initiative.

Work on advanced fuels, including hydrogen, is addressed within the platform. For example, in its 4th Working Group Meeting, the Platform had a session on "Advanced fuels and circular carbon economy" which included presentations exploring coal gasification and the potential role of hydrogen to value domestic coal resources.

As a major beneficiary of the Modernisation Fund[21], Poland considers that this funding should be allocated to investments in line with the climate policy, in order to support the implementation of the NECP's measures, among which hydrogen and fuel cell-related investments. According to its draft Programme of Hydrogen Technology Development, Poland considers the use of hydrogen will serve three main purposes: increasing

[20] https://ec.europa.eu/energy/en/topics/oil-gas-and-coal/EU-coal-regions/coal-regions-transition
[21] Poland expects to consume about 43.41% of the fund financed by the EU ETS allowances

competitiveness of energy companies; increasing energy supply security; maximising gains for the Polish economy in the frame of the energy transition.

Coal gasification is an alternative to its direct combustion, providing a cleaner intermediate energy vector, which can be used to produce power, liquid fuels, chemicals and hydrogen. Specifically, hydrogen is produced by first reacting coal with oxygen and steam under high pressures and temperatures to form synthesis gas, a mixture consisting primarily of carbon monoxide and hydrogen. Currently, the gas produced via coal gasification is mostly used to directly generate power in integrated gasification combined cycle plants (IGCCs). While coal gasification may not be the ideal solution in terms of energy output or efficiency, it may support the transition towards decarbonised hydrogen by supporting the development of hydrogen markets and infrastructure for hydrogen.[22] On the other hand, coal gasification with CCS does not meet the CertifHy threshold of at least 60% emission reduction compared to natural gas based SMR on a lifecycle basis.[23]

For Poland, the EU climate and energy policy will affect the competitiveness of its coal-fired power generation. One of the considered solutions is the shift to "clean" coal. Poland will support national research on clean coal technologies (CCT), including the production of hydrogen from coal gasification, to generate electricity using innovative IGCC (integrated Gasification Combined Cycle), or to use it in fuel cells. Poland considers that the use of clean coal technologies would provide multiple benefits, such as using domestic resources and therefore ensuring greater energy supply security, diversifying raw materials for the domestic chemical industry, and improving Poland's competitiveness.

There have been several projects related to coal gasification funded by the EC in past years, such as:

- **HUGE** – which explored hydrogen oriented underground coal gasification for Europe[24];
- **OPTIMASH** – which aimed to optimise the efficiency and reliability of gasifiers fuelled with high-ash content coal[25];
- **TOPS** – which aimed to develop technology options for coupled underground coal gasification and CO_2 Capture and Storage[26].

Hydrogen in the Ústecký region (Czechia)

The Czech Ústecký region can serve as another illustration of a possible development pathway. The regional government, together with local industry and research organisations, seems to embrace hydrogen technologies as a technological niche that could in the future substitute the regional dependence on coal. Hydrogen is already being produced in the region as a by-product of several chemical facilities but is currently not utilized. The region also hosts several companies that have expertise in gas compression, storage or refuelling technologies[27]. The initial plans for the region are to build first hydrogen refuelling stations in Czechia and to operate a small fleet of hydrogen buses for public transportation within next several years[28]. These demonstration activities would enable participation of local industry and enable later proliferation in other parts of the country.

2.1.4 *Specific national (or regional) hydrogen roadmaps and strategies*

Next to their NECP, several Member States have elaborated, or have announced they will elaborate, other policy documents in which the challenges of hydrogen deployment are addressed in more detail. National hydrogen strategies, roadmaps, or plans are currently being developed by a number of Member States (e.g. AT, DE, NL), while France adopted in 2018 its Hydrogen Deployment Plan for the Energy

[22] http://theconversation.com/explainer-how-do-we-make-hydrogen-from-coal-and-is-it-really-a-clean-fuel-94911
[23] CertifHy (2016) Developing a European guarantee of origin scheme for green hydrogen.
[24] https://cordis.europa.eu/project/rcn/87192/factsheet/en
[25] https://cordis.europa.eu/project/rcn/100981/factsheet/en
[26] https://cordis.europa.eu/project/rcn/109590/factsheet/en
[27] HSR ÚK (2019). Může být uhlí nahrazeno vodíkem?
[28] Český rozhlas (2019). Ústecký kraj chce začít využívat vodík jako energetický zdroj. Počítá s tím tzv. "vodíková platforma".

Transition. Some Member States developed sector specific hydrogen strategies, like Italy with its National Hydrogen Mobility Plan. Other Member States have announced that they will develop specific hydrogen strategies, for instance Estonia and Slovakia (expected by end 2021) and possibly Spain, that considers adopting a specific renewable hydrogen plan.

Several Member States include hydrogen into other policy frameworks. Portugal announced the integration of hydrogen into its industrial policy, Finland and Sweden highlighted the key role of hydrogen in their respective National Energy and Climate Strategies. Other Member States have included or plan to include hydrogen within broader strategies, plans or R&D programmes, like Bulgaria (Innovation Strategy for Smart Specialisation), and Croatia (National Energy strategy). Some Member States foresee to prepare and implement dedicated RD&I programmes, like Poland with its Hydrogen Technology Development Programme.

Some regions are also specifically active in the hydrogen domain and some of them are preparing their own roadmaps, like the Auvergne-Rhône-Alpes region in France deploying hydrogen mobility; the Dutch provinces of Groningen and Drenthe have turned their region into the first "hydrogen valley" in view of becoming a springboard for the hydrogen economy; or the Tees Valley and Leeds City Region in the UK which aim to decarbonize their heating, transport and industry sectors by a massive shift to hydrogen.

Maritime and industrial ports are considered by several Member States as catalyst for the deployment of hydrogen ecosystems, like in Belgium, Estonia, Portugal (Sines) and Spain (Valencia).
Portugal plans to promote energy storage on islands, to enhance security of energy supply and reduce the use of fossil fuels, by increasing the local production of renewable electricity and gases.

Box 2-3 Hydrogen as an adequate option for islands

Islands are in general less interconnected than the mainland and often largely dependent on imported fossil fuels. While most islands have in general a large potential for variable renewable electricity production, they may have no possibility to export excess renewable electricity output to neighbouring territories. Therefore, in these particular cases, there may be an opportunity for producing hydrogen through electrolysis using renewable electricity and storing the produced hydrogen or using it, e.g. for transport purposes. Deployment of renewable hydrogen technologies could decarbonise the energy supply of islands and substantially contribute to their energy independence and security of energy supply.

The **island of Orkney** has for instance decided to use its surplus of renewable electricity for hydrogen production. Orkney has developed an 'Orkney Hydrogen Economic strategy' which contributes to reaching UK's sustainability targets and puts Orkney at the forefront in the energy transition. According to the Orkney Islands Council[29], generating hydrogen in Orkney has the potential to turn a challenge into an opportunity by:

- Reducing curtailment of local renewable energy production to maximise renewable energy resources' use;
- Alleviating the loss of revenues for local energy producers;
- Reducing negative impacts to marine energy innovation;
- Participating in hydrogen projects along with a wide variety of partners from Europe (BIGHIT, S'N'T, Dual Ports, On-board vehicle electrolysers);
- Supporting Orkney communities and companies;
- Developing training opportunities provided locally by Orkney College defining the standard excellence in Hydrogen industry standards;
- Attracting wider investment to the local area;

[29] https://www.orkney.gov.uk/Service-Directory/Renewable/h2-in-orkney-the-hydrogen-islands.htm

- Leading the way for other territories to replicate a hydrogen economy.

BIGHIT, for example, is an ongoing FCH JU funded project in Orkney that aims to implement a fully integrated model of decarbonised hydrogen production, storage, transportation and utilisation for heat, power and mobility, while absorbing curtailed energy from wind and tidal turbines.[30]

In order to increase its security of energy supply and reduce the use of fossil fuels, Portugal plans to promote energy storage, especially in its islands with isolated electricity networks, by implementing pumped hydro systems, batteries and hydrogen technologies, which will also facilitate a significantly increased local production of variable renewable electricity. By 2030, Portugal will implement smart electricity grids to strengthen the stability and resilience of small-scale isolated electricity systems and facilitate an increased penetration of variable renewable energy sources.

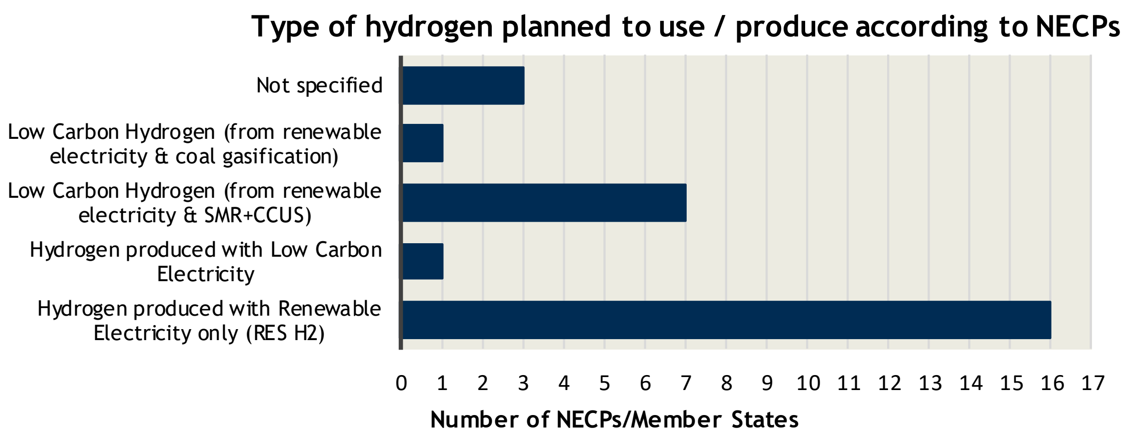
In Greece, several islands will remain disconnected from main energy infrastructure. Although Greece in its NECP does not specifically address hydrogen as a possible option, the installation of renewable hybrid plants will be promoted combining production with storage. Hydrogen could be one of the suitable hybrid technologies. The 'Clean energy for all Europeans' package[31] provides a long-term framework to help islands generate their own sustainable, low-cost energy. Hydrogen could be promoted in this framework.

2.2 Hydrogen related targets, initiatives and policy measures in the NECPs

2.2.1 *Most NECPs refer to Hydrogen generation via electrolysers using renewable electricity*

According to the large majority of EU Member States, decarbonised hydrogen should mainly be produced by electrolysers using renewable electricity (as illustrated in Figure 2-2). The production of low carbon hydrogen through other pathways, such as Steam Reforming Methane using fossil fuels coupled with CCU or CCS, is considered as a transitory option by some Member States like Austria (only considering CCU), Belgium, Croatia and the Netherlands, while other Member States, like Ireland and the United Kingdom, would consider this option also in the long term. According to its NECP, Poland assesses the potential to produce hydrogen via coal gasification, for use in innovative power plants (Integrated Gasification Combined Cycle), or in fuel cells. France intends to produce hydrogen via electrolysers using low carbon electricity (from renewable energy and nuclear plants), with the aim to progressively increase the share of renewable electricity as input energy.

Figure 2-2 Number of Member States indicating in their NECP the type of hydrogen they plan to use/produce



[30] https://www.fch.europa.eu/project/building-innovative-green-hydrogen-systems-isolated-territory-pilot-europe
[31] https://ec.europa.eu/energy/topics/renewable-energy/initiatives-and-events/clean-energy-eu-islands_en

Renewable hydrogen is in several NECPs considered as a link between the electricity, heating and cooling in the built environment, transport and gas sectors, supporting the integration of higher volumes of variable renewable electricity into the system by providing system flexibility.

Given their limited potential to domestically produce low carbon hydrogen, some Member States seem to consider importing low-carbon or renewable hydrogen. Other Member States with a large technical potential for variable renewable electricity production, consider becoming renewable hydrogen exporting countries, like Portugal, and possibly Malta (in the long term) and Spain. Several projects and initiatives are being considered to connect different regions and countries, aiming to produce renewable hydrogen in areas with large off-grid wind or solar energy parks (e.g. in South-East Europe) and to transport it to hydrogen using countries or regions (e.g. the Interreg Danube Transnational region). The IPCEI project Green Hydrogen @ Blue Danube is developed with the aim to facilitate connecting hydrogen producing areas with hydrogen consuming areas. The Portuguese project at Sines is also set up in view of producing hydrogen for export purposes.

According to the NECPs, the large majority of EU Member States foresee to support hydrogen production demonstration and pilot projects in their R&D programmes and budgets, in view of large scale sector integration and/or development of hydrogen ecosystems or valleys (e.g. IE, DK, NL, UK).

2.2.2 Several NECPs refer to the intention of using existing methane infrastructure for hydrogen and of setting up a market for hydrogen

Several Member States (AT, EL, HU, IE, IT, PT, SL, SK, UK) consider that greening the gas supply by gradually replacing natural gas with biogas, biomethane, hydrogen and synthetic methane from renewable energy sources, is a key component in the transition to a decarbonised energy system. Some Member States (e.g. FR) have determined specific targets for the share of renewable gas in the gas mix by 2030.

Several NECPs acknowledge that hydrogen has a key role to play in decarbonising the gas sector while contributing to security of energy supply. Hungary is for instance considering that renewable hydrogen could progressively replace the production and use of biogas, while this is in general still considered as the first option to ‘green’ the gas mix.

Some Member States, like Czechia, Hungary, the UK and Poland, explicitly refer to the role of hydrogen to decarbonise the heating sector by distributing hydrogen via the existing methane network.
Several Member States (e.g. Latvia, Greece, Portugal, Slovenia, Spain) mention their intention to set up adequate market conditions for hydrogen and/or other renewable gases. Some Member States, like Greece and Portugal, explicitly refer to the Guarantees of Origin system as an appropriate measure to stimulate the deployment of biogas and renewable hydrogen. Others, like Italy, consider introducing a mandatory quota for renewable gases (including hydrogen).

Several Member States, among which Italy, France, Greece, Spain and Slovenia, consider that the existing natural gas infrastructure will be of vital importance for the energy system, to facilitate the development of renewable electricity and gas (biomethane, hydrogen and synthetic methane), to ensure security of energy supply and to boost the use of alternative fuels in the transport sector. To this end, some Member States consider more inter TSO coordination of investment plans, as well as further research regarding the possible use of methane infrastructure for hydrogen. Some Member States like Italy, Greece, Latvia, Lithuania, Spain and Slovenia mention their intention to assess the possibility of refurbishing their natural gas infrastructure in order to enable the transport and distribution of hydrogen. Other Member States, like Malta, are planning new gas infrastructure, and are tapping future opportunities such as the supply of biomethane or renewable hydrogen blended with natural gas.

According to their NECPs, several Member States like Belgium, Estonia, France, Italy, Latvia and Slovenia plan to further analyse the impact of blending hydrogen into the natural gas infrastructure on the network as well as the different types of end-users, in view of establishing appropriate technical and regulatory specifications to facilitate the injection of hydrogen.

Several NECPs refer to the intention to use existing transport and distribution methane networks to store and deliver renewable hydrogen produced from 'excess' electricity supply; some NECPs refer to the need to integrate electricity and gas system operations and to also take into account the capacity deployment in neighbouring countries. In several Member States, in particular Italy, Germany, France, the Netherlands and Romania, gas TSOs have announced their intention to convert and deploy their methane infrastructure for hydrogen transport.

Regarding hydrogen storage, several Member States (e.g. Germany, France, the Netherlands and the UK) have geological salt caverns on their territory that are used for natural gas storage and consider using (part of) this storage capacity for hydrogen generated from power-to-gas installations. Spain intends to adapt part of its existing LNG storage capacity to allow hydrogen storage. The potential use of possibly suitable underground salt layers for hydrogen storage is explored by different Member States (e.g. Austria, Denmark, Poland and Slovakia).

2.2.3 Transport is in most NECPs considered as the first market segment to deploy hydrogen

Several Member States mention in their NECP that the share of hydrogen in their national transport system is expected to gradually uptake by 2030. Some NECPs include specific objectives, but they remain general rather global, e.g. total hydrogen demand from transport (BG, HR, PT, SL), share of hydrogen in total transport fuel consumption in 2030 or 2040 (BE, DE, HU), or share of renewable energy in total transport fuel consumption in 2030 (IT, SK). Some Member States, like France and Czechia, have fixed a number of hydrogen fuel cell vehicles by 2030. Several Member States consider the development of fuelling infrastructure a necessary prerequisite for the market development of hydrogen fuelled vehicles, and some of them (like Belgium, Czechia and France) have fixed concrete targets for the number of refuelling stations to be built by 2030. Some Member States like Croatia also explicitly refer to their intention to develop technical standards to facilitate the market uptake of hydrogen-driven vehicles.

Some Member States, like Belgium, aim at making their public transport fleet more sustainable (e.g. purchase of buses on hydrogen, electricity or hybrid), by switching to alternative fuels for public transport or by adapting public procurement procedures allowing only zero- or low-emission vehicles. Belgium is also making financial resources available to support the use of hydrogen for trucks.

Some Member States with high GHG emission reduction targets, like Denmark or Italy, intend to, promote low carbon solutions including hydrogen, in the heavy duty road, railway, aviation and navigation sectors. Other Member States, like Malta, consider battery electric driven systems to be used for passenger cars, while hydrogen fuel cell technology is expected to be used for heavy duty road transport (trucks and buses).

2.2.4 Industry is the second target sector for hydrogen use

Several Member States (AT, BE, HR, DK, FI, FR, DE, HU, NL, PT, SK, SE, UK) mention in their NECP that renewable or low carbon (SMR / CCUS) hydrogen is expected to gradually and partially replace the use of fossil-based hydrogen or natural gas as feedstock in the industry, mainly in the oil refining, steel, ammonia, fertilisers and pharmaceutical sectors.

The iron and steel sector is studying new applications for low carbon hydrogen, mainly in Austria, Germany, Finland and Sweden. France is the only Member State that has mentioned a concrete objective in its NECP; it foresees to switch 20 to 40% of fossil-based hydrogen in industry by hydrogen produced in electrolysers using low carbon electricity by 2028.

A limited number of Member States are specifically referring to the use of hydrogen for power generation; Portugal plans to assess the conversion of 2 coal-fired power plants to renewable hydrogen; Hungary considers using hydrogen in conventional gas engines or turbines after their conversion; and Poland foresees to generate electricity using hydrogen in IGCCs.

2.2.5 NECPs refer explicitly to the need for further R&D and to national commitments in this domain

Almost all Member States refer in their NECP to R&D as a key pillar to ensure the competitiveness of hydrogen applications in the medium and long term, by improving the technologies, in particular the efficiency of electrolysers, storage material, etc. through pilot and demonstration projects. NECPs refer to the required (and expected) reduction in the cost of electrolysis technology, which should, in parallel with the large availability of renewable electricity at low cost, contribute to reaching competitiveness for renewable hydrogen.

Several Member States (e.g. Austria, Belgium, Czechia, Denmark, France, Germany, Greece, etc) consider hydrogen as a priority topic in the research agenda for the energy transition, and recognise the need for increased funding, especially in view of facilitating demonstration projects and market uptake.

In Member States, RD&I is addressed through dedicated hydrogen specific programmes and related budgets, while other Member States are adapting their innovation programmes (or strategies) in view of including a clear focus on hydrogen and fuel cells related activities. Almost all Member States expressed their intention to support hydrogen related demonstration projects.

Research organisations are in general closely collaborating with the industry on hydrogen and fuel cell related initiatives, at national and EU levels (e.g. through Horizon 2020, SET-Plan, …).

2.2.6 Several NECPs refer to supra-national cooperation on hydrogen related research and industrial initiatives

Several Member States consider it is useful to address hydrogen in the frame of regional cooperation in research and in developing infrastructure, policy instruments and regulation.

As an example, the Ministers of Energy of the Pentalateral Energy Forum, consisting of Austria, Belgium, France, Germany, Luxembourg, the Netherlands and Switzerland, confirmed in a Political Declaration[32] their intention to maintain and strengthen their cooperation in the framework of the NECPs. In particular, policy instruments and measures with substantial cross-border effects are discussed in the new Pentalateral-NECP Committee such as flexibility options, including energy storage, demand side management, power-to-x, integration of electric cars and the possible development of hydrogen. As a first step, the Forum organised a workshop to define cooperation topics on hydrogen. The concerned countries intend to examine common approaches for guarantees of origin, cross-border infrastructure, the respective role of TSOs and DSOs and standards for hydrogen injection. They also intend to exchange information and best practices on support schemes for hydrogen and innovation projects and on the future role of hydrogen in general.

Latvia and other Nordic-Baltic Member States intend to include the use and deployment of hydrogen in the list of topics to be addressed in the frame of the Nordic-Baltic cooperation. Collaboration projects already exist, like the Baltic Sea Region Hydrogen Network project (financed by the Swedish Institute) with the aim to "*build an extensive, multinational, multilevel and cross sectoral network/partnership regarding Hydrogen around the Baltic Sea, which subsequently will mobilize early users and increase awareness of Hydrogen as an energy carrier in the Baltic Sea Region*".
Five Member States (Austria, France, Germany, Italy, and Netherlands) and the United Kingdom participate in Mission Innovation, especially in Innovation Challenge no 8 on renewable and low-carbon hydrogen[33], supporting the participating countries to accelerate the development of a global hydrogen market by identifying and overcoming key technology barriers.

The Netherlands and the European Commission participate in the new Hydrogen Initiative[34], under the Clean Energy Ministerial (launched at CEM10 in Vancouver, Canada), will drive international collaboration on policies, programs and projects to accelerate the commercial deployment of hydrogen and fuel cell technologies across all sectors of the economy.

Five Member States (Germany, Austria, Netherlands, France and Italy), United Kingdom and the European Commission participate in the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), which mission is to facilitate and accelerate the transition to clean and efficient energy and mobility systems using hydrogen and fuel cell technologies across applications and sectors.

2.3 Conclusions and good practices based on the NECPs' assessment

2.3.1 *Main conclusions*

According to the NECPs, most EU Member States recognise the potential key role of renewable and/or low-carbon hydrogen in the transition to a decarbonised economy, and by and large have adopted one of the two following approaches to facilitate its uptake: some Member States have determined a set of specific objectives, policies and measures for low-carbon technologies and fuels, including hydrogen (most common approach) while other Member States have fixed ambitious overall decarbonisation

[32] https://www.benelux.int/files/8115/5179/5132/politiekeverklaring4maart.pdf
[33] The Challenge is co-led by Australia, the EC and Germany with participation from Austria, Canada, Chile, China, France, India, Italy, Japan, the Netherlands, Norway, Saudi Arabia, UK and USA.
[34] http://www.cleanenergyministerial.org/initiative-clean-energy-ministerial/hydrogen-initiative

targets and implemented economy-wide and technology-neutral instruments (approach mainly adopted by the Nordic countries).

Generally, in their NECP, Member States did not elaborate their approach towards hydrogen in a comprehensive and structured way. This is partly related to the fact that the NECP template imposed by the concerned Regulation does not foresee specific sections per energy vector, but rather main cross-vector sections (according to article 3 of the Regulation) and specific cross-vector sections that present the main objectives, targets and contributions to the five dimensions of the Energy Union (article 4). The possible contribution of hydrogen could hence be referred to in different sections of the NECPs. As a specific exhaustive section on hydrogen in the NECP would not be compliant with the Regulation, Member States could consider to develop a dedicated policy document for hydrogen (strategy, plan or roadmap), that should preferably be comprehensive and could address the different aspects of the value chain.

While most NECPs refer to the importance of hydrogen in the energy transition, only few mention concrete steps, such as specific objectives, or demand related measures or enabling regulatory interventions to address the barriers in a comprehensive way. The deployment of specific hydrogen infrastructure or adaptation of existing methane infrastructure is mentioned in several NECPs, but it is in most cases not yet addressed from a national or supra-national perspective, but rather focusing on research and pilot projects. A more comprehensive approach can possibly be expected in the next edition of the NECPs (due by end 2025). The current NECPs are a first positive step showing the political interest of most EU Member States to integrate hydrogen in their energy system and end-uses. They strongly focus on research, large scale demonstration and pilot projects, which is indeed the required next step to improve the competitiveness of hydrogen technologies and prepare their market uptake. In this context, the different existing and planned projects and initiatives (e.g. IPCEI, Horizon 2020, nationally funded projects, …) referred to in the NECPs, are essential to acquire the required knowledge and spur hydrogen applications to market uptake. Private market operators and research organisations play a central role in this development, while coordination and support from authorities accelerates the progress.

The Nordic approach (technology and energy vector neutral policy) can generally be considered efficient and appropriate to speed up decarbonisation by using all mature low-carbon technologies. However, two challenges might need more targeted action: 1) ensuring the development of adequate hydrogen transport and supply infrastructure, and 2) ensuring that promising hydrogen applications are reaching maturity and competitiveness. While for the first challenge, energy vector specific government initiatives might be necessary, the second challenge is mainly addressed through more global, energy vector neutral measures; in particular, the ambitious GHG reduction target imposed in these Member States and the application of a high carbon tax, which will help renewable and low-carbon hydrogen to compete with fossil fuels on the medium term. The public measures are also reinforced by ambitious private commitments (e.g. steel industry to become net-zero emitter by 2026, Scandinavian Hydrogen Highway Partnership to build the hydrogen refuelling stations' corridors). The public authorities support these initiatives, by providing Innovation funds or by addressing specific regulatory barriers.

Box 2-4 SHHP - Scandinavian Hydrogen Highway Partnership[35]

The Scandinavian Hydrogen Highway Partnership - Showing a multitude of pathways for hydrogen supply using local resources

The Scandinavian Hydrogen Highway Partnership (SHHP) was established in 2006, when the different Nordic hydrogen organizations joined forces to coordinate the market introduction of hydrogen cars and HRSs to the Nordic market.

At the same time, SHHP has been hosting the recurring conference HFC Nordic, which is held every second year in a Nordic country, last time in 2018 in Iceland. Next time will be in Denmark in the city of Aalborg.
SHHP consists of regional clusters involving major and small industries, research institutions, and local, regional and national authorities. The national networking bodies – Norsk Hydrogenforum in Norway, Hydrogen Sweden in Sweden, Icelandic New Energy in Iceland, Brintbranchen in Denmark and VTT in Finland – act as SHHP coordinators.

The cooperation focus on maintaining a good dialogue with car, truck and bus manufacturers as well as politicians to ensure continued expansion of the Nordic hydrogen infrastructure.
All activities are based on effective collaboration across the borders and are backed with strong public and private support in terms of funding, attractive financial tax exemption schemes and investments. Our goal is to create one of the first regions in Europe where hydrogen is available and used in a network of refuelling stations.

2.3.2 *Good practices identified in the NECPs that can serve as guidance for preparing national hydrogen roadmaps*

Based on the analysis of the NECPs and other hydrogen related policy documents, this section proposes a template for the preparation of national hydrogen roadmaps or strategies. It can also be used to guide the integration of hydrogen into a broader energy or industry policy framework, and comprises the following steps:

1. Assessment of the current situation, identifying existing barriers, main industrial and research actors, current initiatives and expertise on the national territory;
2. Identification of long-term expectations, potential developments and role of hydrogen in the energy system, recognizing the versatility of hydrogen and how it can provide low carbon and competitive solutions to different sectors;
3. Definition of the short-term and long-term objectives, planning the major milestones;
4. Setting up of the required institutional framework to ensure effective cooperation among the different stakeholders from all concerned sectors, including the decision makers;
5. Setting up of concrete policies and measures, and defining the resources needed.

Current situation, barriers and stakeholders

The first step would be to establish a clear status of the existing situation regarding hydrogen production, infrastructure for transport, storage, distribution and delivery, number of fuel cells used in transport and buildings, industrial use of hydrogen. The Member States' fiches can serve as a basis for such an analysis.

Industry and research institutions should be involved in a coordinated way, which seems to be the case in several Member States, among which Estonia, Germany, Ireland, Italy, the Netherlands and the

[35] http://www.scandinavianhydrogen.org/shhp/about-shhp/

United Kingdom. Assessing the strengths and opportunities of the existing infrastructure and industry at national level would be key to defining the pathway for the deployment of new hydrogen and fuel cell related economic activities.

Several Member States have participated in the HyLaw[36] project, that identified and assessed major regulatory barriers, in view of prioritizing measures to address them. This study outcome can serve as basis to reflect on concrete measures in the concerned Member States. The countries that did not participate in the project, could carry out similar assessment to identify their national specific barriers to the deployment of hydrogen.

Long term expectation and potential role of hydrogen in the energy system

As a versatile energy carrier, hydrogen can play a role in different sectors. It is therefore key to address hydrogen from a holistic perspective and taking into account its complementarities with other technologies (e.g. Denmark and France refer in their NECP to the complementarity between batteries and power-to-hydrogen), or to focus on a specific area where potential producers (e.g. wind parks coupled with electrolysers and storage) can be coupled with a cluster of hydrogen users (e.g. deploying a hydrogen valley). Several Member States refer to the opportunities offered by hydrogen in the context of sector integration, but in their NECPs they are not always directly addressing concrete pathways to effectively value these opportunities (e.g. will they promote coupling large-scale wind parks with electrolysers producing hydrogen to be transported to end-users and/or installing decentralised electrolysers to cover the flexibility needs of the electricity system?).

A clear distinction should be made between the short-term deployment and the long-term vision, based on the applications' maturity and the deployment of the required infrastructure, thus allowing a step by step approach to be prepared.

The most mature applications are briefly addressed in the majority of the NECPs, while a more in-depth reference to industrial trends or more detailed information is available in specific roadmaps or other policy documents, e.g. the Netherlands in its Climate Agreement, announced a hydrogen programme which will focus on unlocking the supply potential of green hydrogen (3 to 4 GW electrolyser capacity by 2030), developing the necessary infrastructure (roll-out of a hydrogen infrastructure in the industrial clusters), cooperating with end-use sectors, and facilitating ongoing initiatives and projects.

Enabling institutional framework

A dedicated national organisation may help in the gathering of concerned authorities, industry, SMEs and research institutions, to address research, regulatory and market issues. It can take the form of a steering or working group set up by authorities, a specific agency or association and/or a dedicated team within the energy ministry. Several Member States have set up such a specific structure; some of these national initiatives are hereafter presented as 'good practices'.

In Germany, NOW GmbH coordinates and steers the Federal Government's National Innovation Programme (NIP) for Hydrogen and Fuel Cell Technology and the funding guidelines on charging infrastructures. NOW is also involved in the development of the overall hydrogen strategy and is responsible for coordinating and managing the German government's initiatives related to hydrogen and

[36] https://www.hylaw.eu/

fuel cells (the NIP on Hydrogen and Fuel Cell Technology, the Electric Mobility and Charging Infrastructure funding guidelines, the further development of the Mobility and Fuel Strategy[37], the implementation of the EU Directive 2014/94/EU, etc.).

Italy has set up a specific Hydrogen Working Group, where 31 multi-company or transversal project proposals have been presented and discussed. The Working Group will spur a feasibility analysis of the proposed initiatives in view of their industrial development and will study the various regulatory aspects relating to the hydrogen supply chain. Estonia has also set up a working group with the aim to analyse the deployment of hydrogen and fuel cells applications and to prepare a hydrogen roadmap.

Croatia will establish a hydrogen technology platform, bringing together national stakeholders from research and industry. In Ireland, HydrogenIreland (H2IRL), the national association acting as a forum for the hydrogen community, aims to bring together industry, universities, research institutes and policymakers to initiate and coordinate activities related to hydrogen.

Private hydrogen associations exist amongst others in Belgium, the Netherlands, Latvia and Poland; they act as a platform for information exchange and sensibilisation and can already support decision makers to develop a hydrogen strategy and roadmap.

Coordination and collaboration with neighbouring countries and other EU Member States are also essential, for instance when addressing hydrogen refuelling stations deployment in view of realising corridors at multinational level, cross-border issues related to hydrogen pipelines (back-bones), renewable gas market harmonisation, certification schemes, specifications and standards for end-use appliances. In this context the cooperation structures referred to in the NECPs between national authorities (e.g. Pentalateral Energy Forum, Nordic-Baltic cooperation framework) and between market operators and research institutes (e.g. multinational cooperation in the context of Horizon, IPCEI projects) can be considered as good practices.

Defining specific hydrogen related objectives at national level

To effectively stimulate the deployment of hydrogen, defining clear objectives for 2030 and beyond might be an important step. In principle, sub-objectives per energy vector or per market segment are not necessary for mature low-carbon technologies; they should indeed compete on a level playing field to reach the overall energy and climate targets at least cost. As renewable and low-carbon hydrogen technologies have not yet reached maturity, concrete vector specific objectives might still be useful to improve their competitiveness and facilitate their market introduction. In this context, setting national objectives can be considered as a good practice. Objectives should ideally be quantitative but can also be qualitative, and can address all or specific value chain components, covering production, transport, storage, distribution and end-use in the different sectors.

Some NECPs mention quantitative targets regarding the production of renewable hydrogen in 2030, while others mention targets or estimates for renewable or low-carbon hydrogen demand in 2030, mainly focusing on the transport sector:

- Austria has mentioned in its NECP that the renewable electricity-based hydrogen consumption should reach 1.11 TWh in 2030;

[37] https://www.vda.de/en/topics/innovation-and-technology/fuel-strategy/the-mobility-and-fuel-strategy.html

- In Belgium, 1% of passenger cars in Wallonia should by 2030 be hydrogen fuelled and Flanders aims to have 50% zero emission new light vehicles in 2030;
- Bulgaria expects by 2030 an annual hydrogen consumption of 32 GWh in the transport sector;
- Croatia expects for 2040 a hydrogen consumption of 2.8 GWh in the transport sector and 3.5% low carbon vehicles by 2030;
- Czechia's goal is to have 40 000 – 50 000 fuel cell electric vehicles, 870 buses and 80 refuelling stations by 2030;
- France is committed to have by 2028 20 000 - 50 000 light duty and 800 - 2 000 heavy duty fuel cell vehicles, as well as 400 - 1 000 hydrogen refuelling stations. Further, the switch of 20 to 40% of fossil-based hydrogen in industry to hydrogen produced in electrolysers using low carbon electricity is foreseen by 2028;
- Germany expects to cover about 0.1% of its transport needs with hydrogen by 2030, and around 0.2% by 2040;
- Hungary mentions in its NECP that about 1% of its transport needs would be covered by hydrogen in 2030, and around 5% in 2040;
- Italy has the ambition to reach around 1% of its renewable energy target for transport by using hydrogen fuelled cars, buses, heavy goods vehicles and trains, and eventually sea transport, or by injecting hydrogen into the methane network, including for transport use;
- the Netherlands has the ambition to have an installed electrolyser capacity of 3-4 GW in 2030, and mobility targets of 50 tank stations, 15 000 FCEVs and 3 000 hydrogen trucks in 2025. In 2030 it is expected to have 300 000 hydrogen vehicles in total;
- Portugal expects by 2030 a final renewable hydrogen consumption of 756 GWh in the transport sector, representing about 7% of the renewable fuel consumption for transport;
- Slovenia expects by 2030 a final hydrogen consumption of 116 GWh in the transport sector, and by 2040 a consumption of 732 GWh mainly in the transport, but also progressively in the building and industry sectors. Slovenia also expects that, by 2030, about 10% of the national gas consumption would come from renewable sources (biomethane, hydrogen and/or synthetic methane - from hydrogen methanation);
- Slovakia estimates that by 2030 around 1% of its RES target for the transport sector will be covered by the direct use of hydrogen (about 23 GWh out of a total of about 2 663 GWh renewable fuels). By 2040, this share could be multiplied by more than 20.

The industry sector was only addressed in the NECP of one Member State, while the building and power sectors were in general not explicitly referred to in the target setting. The NECPs do also not contain concrete objectives or perspectives regarding the deployment of specific hydrogen storage capacities.

Nearly all Member States refer in their NECP to the importance of RD&I to enable a competitive deployment of renewable and low-carbon hydrogen. Some NECPs mention specific qualitative (e.g. referring to hydrogen as focus area) or quantitative (e.g. dedicated budget) objectives.

Policies and measures mentioned in the NECPs that stimulate hydrogen deployment

Several NECPs refer to a specific hydrogen roadmap or strategy document, which has been or will be elaborated at national level. When preparing such a dedicated hydrogen roadmap, we suggest to first assess existing policies and measures having an impact on the building and operation of hydrogen production assets, the deployment of transport, storage and delivery infrastructure and of end-use applications. Where deemed necessary, generic policies, measures and instruments can be adapted to specifically consider hydrogen applications. As an example, the most common instrument used by many Member States consists of fiscal or financial measures for vehicles or differentiated tax levels for transport fuels in order to incentivise the acquisition of low carbon vehicles and/or the use of low-carbon fuels. Depending on the scope and modalities of such fiscal or financial instruments, they can stimulate or hamper the use of hydrogen compared to other low-carbon alternatives.

The analysis of the NECPs shows that several Member States have included, explicitly or implicitly, hydrogen in their national policies, or have taken or intend to take specific measures for hydrogen. The following list provides a selection of measures or initiatives that are mentioned in the NECPs:

- Austria foresees to address the legal framework for renewable gases (including hydrogen), and to exempt renewable gases from taxation;
- Belgium provides financing instruments (Wallonia) and considers setting up a support scheme (Flanders) in order to stimulate the installation of hydrogen refuelling stations;
- Bulgaria intends to support a pilot demonstration project for hydrogen production with a total installed capacity of 20 MW;
- Croatia plans to provide financial incentives for energy-efficient vehicles (including hydrogen-driven), to develop alternative fuels infrastructure and elaborate the required technical specifications;
- Czechia exempts vehicles with emission factors lower than 50 g CO_2/km (including hydrogen-driven) from registration fees and highway tolls since the beginning of 2020;
- Denmark provides grants to two power-to-X demonstration projects for production and storage of renewable hydrogen, to demonstrate production and consumption on near market-based conditions. Denmark has also set up a dedicated fund to support development and demonstration projects on energy storage (17 million EUR);
- Finland has set up a CO_2 pricing mechanism in 1990 and has introduced a carbon related taxation for vehicles. Finland also foresees to promote the purchase of hydrogen-powered vehicles so that the share of new technologies in the vehicle fleet can be brought up to a level that is adequate for creating a well-functioning market;
- France intends to take new regulatory and market measures (more information is provided in its hydrogen plan[38]) to pave the way for 'decarbonised hydrogen' in the industrial, transport and gas sectors. France intends to implement a support scheme with a budget of 100 million EUR (through tendering for hydrogen mobility and low carbon electrolysers projects);
- Germany intends to invest 100 million EUR annually in research related to hydrogen technologies;
- Greece considers the system of Guarantees of Origin for biogas and hydrogen as an appropriate measure to stimulate the use of renewable gases. Greece intends to participate in RD&I initiatives for the shipping sector;
- Hungary plans to establish appropriate conditions (including safety) and incentives necessary to feed in hydrogen in the natural gas system;
- Italy considers introducing a mandatory quota for renewable gases (including hydrogen) and to establish enabling rules for injection of hydrogen into existing natural gas infrastructures;
- Latvia foresees to develop an action plan for the deployment of hydrogen infrastructure, while also taking actions to set up adequate market conditions;

[38] https://www.ecologique-solidaire.gouv.fr/sites/default/files/Plan_deploiement_hydrogene.pdf

- Luxembourg will in the context of its direct grant programme subsidize the purchase of hydrogen fuel cell vehicles;
- Poland will in the context of its Low-Emission Transport Fund (PLN 6.7 billion for the 2018-2027 timeframe) support the development of alternative fuels. In this frame, Poland also intends to support educational programmes for renewable fuels, including hydrogen;
- Portugal aims to create enabling conditions and mechanisms to deploy hydrogen by: (i) regulating the injection of renewable gases into the natural gas network, (ii) implementing a guarantees of origin system for renewable gases, (iii) mobilizing financial resources to support renewable hydrogen production, (iv) assessing the implementation of binding targets by 2030 to incorporate renewable gases into the natural gas network. Portugal also plans to assess the conversion of 2 coal-fired power plants to renewable hydrogen;
- Romania supports the demand for low emission vehicles and the use of ecological fuels through the application of a tax reduction for low carbon vehicles (including hydrogen);
- Slovenia intends to focus its R&D activities, among others, on analysing the impact of blending renewable hydrogen with natural gas on the methane network and on the different types of end-users, and on demonstrating sector integration at scale;
- the United Kingdom has dedicated as £25 million budget for investigating the use of hydrogen for heating and testing domestic gas pipes and appliances.

Some Member States have not included all their hydrogen related policies and measures in the NECP, but have elaborated specific hydrogen strategies or roadmaps, which contain a comprehensive overview of initiatives and targets in this domain.

3 Opportunities for deploying renewable and low-carbon hydrogen technologies

Further decreasing costs for renewable electricity and hydrogen production technologies creates opportunities for Member States to use this option to strengthen their economy and reduce the overall costs of the energy transition towards achieving the Paris Agreement commitments. This chapter assesses these opportunities by focusing on the national potentials for renewable and low-carbon hydrogen production, transport and storage, hydrogen demand and the political and industrial environment to support this deployment.

Hydrogen can be used as energy carrier, fuel or feedstock, and can be transported or stored in liquefied or gaseous form. Its deployment will contribute to energy system stability and security of energy supply, as the production of hydrogen based on local renewable electricity will reduce dependence on fossil fuel imports and help integrate variable renewable energy sources into the system. Hydrogen will also contribute to economic wealth in terms of job creation and added value. Hydrogen can in particular be used to decarbonise difficult to electrify end-uses, such as long-distance and heavy-duty transport, high temperature heat processes in the energy-intensive industry, and the use of fossil fuels as feedstock in the steel and (petro-)chemical industries. In some of these cases, renewable and low-carbon hydrogen may be one of the few feasible decarbonisation options.

The deployment of hydrogen also enables an overall optimisation of the electricity and gas system (sector integration) by converting renewable electricity into hydrogen and storing and distributing it via the gas system, while contributing to the stability of the electricity system. This development will enable continued use of existing methane infrastructure, either by blending hydrogen with natural gas into existing networks, or by refurbishing part of the networks or storage facilities to dedicated hydrogen use. This option will also reduce investments to reinforce the electricity system, facilitate the integration of renewable electricity into the market, and reduce curtailment of renewable electricity production.

3.1 Hydrogen production potential and its role in energy system flexibility

3.1.1 Context

The production potentials for renewable and low-carbon hydrogen largely differ per Member State; the first is mainly dependent on the availability of renewable electricity, whereas the latter is dependent on the availability of fossil fuels and suitable sites for CO_2 storage. The technical potential for variable renewable electricity generation is in all EU Member States except Luxembourg, larger than their expected national electricity demand in 2030; most Member States have hence a technical potential to build up dedicated renewable electricity generation capacities to produce hydrogen via electrolysis.

A specific opportunity for hydrogen production using electrolysis is identified in countries that utilize nuclear energy. The electricity produced in nuclear power plants typically covers the “base load”, since these power plants have comparatively low variable costs. As the flexibility of nuclear power plants is limited and taken into account that they need a high load factor in order to cover their fixed costs, their power output not utilizable on the power market could be converted into low-carbon hydrogen.

Low-carbon hydrogen can be produced from fossil fuels (mostly natural gas, while Member States with domestic coal resources could consider using coal gasification), combined with carbon capture, use or storage (CCUS). The potential of carbon capture and use (CCU) is not specifically considered in this opportunity assessment, but the CCS potential is evaluated on the basis of the country's availability of CO_2 storage capacity as well as existing knowledge in CCS deployment.

The assessment looks also at the potential role of power-to-hydrogen conversion and hydrogen storage in the provision of energy system flexibility. The shift in most Member States to an electricity system largely based on non-dispatchable (variable) renewable energy sources, such as wind energy and PV, leads to high fluctuations in electricity supply, which generate challenges for balancing supply and demand. The increasing flexibility needs can be covered by hydrogen-based solutions (next to flexible electricity generation, energy storage, interconnection capacity and demand-response). Hydrogen can also substitute natural gas demand from dispatchable power generation units needed for covering flexibility needs. While power-to-hydrogen conversion and hydrogen storage can effectively contribute to decarbonising and balancing the electricity system, the economic feasibility of electrolysers largely depends on the investment cost and conversion efficiency, which are both expected to improve in the coming years, as well as on the availability and cost of electricity, which also have a huge impact on their load factor and competitiveness.

Box 3-1 Specific opportunity for offshore hydrogen production in the North and Baltic Sea

Artificial islands dedicated to hydrogen production

A specific opportunity for hydrogen production might arise as a solution to the economic and technical challenges of connecting offshore wind farms to the electricity grid. In the case of a significant offshore wind capacity build-up, transmitting the large amounts of energy generated in the North and Baltic Sea to the consumers is challenging. This would require the construction of transport lines to the shores and subsequent adaptations of inland network to be able to transmit the electricity to major consumption centres. One of the potential solutions being discussed is building artificial islands off the Sea coast to set up electrolysers or methanation systems powered by wind energy. Green hydrogen produced in such a way would facilitate the implementation of long-term storage solutions and the decarbonisation of industrial and transportation sectors.[39]

The **North Sea Wind Power Hub (NSWPH)**[40] consortium[41] is developing technical concepts for supplying the capacities required to generate energy from renewable sources at the lowest environmental impact and cost. The planned wind power capacities in the North Sea range from 70 to 150 GW by 2040 and up to 180 GW by 2045. The consortium aims to develop several hubs that will act as central platforms for supporting the infrastructure required to transport the energy, e.g. for converting electricity into gas (in particular green hydrogen) instead of using the offshore converter platforms currently in place. The aim is to facilitate the large-scale roll-out and integration of far North Sea offshore wind parks in the energy system at least overall cost while contributing to security of energy supply, energy markets' integration, competitiveness and decarbonisation of energy supply. The approach is based on an internationally coordinated rollout of Hub-and-Spoke projects to connect wind power parks to energy users through an optimal mix of infrastructure, including power-to-hydrogen installations.

[39] https://www.h2-international.com/2019/05/06/hydrogen-islands-in-the-north-sea/
[40] northseawindpowerhub.eu
[41] TenneT, Energinet, Gasunie and Port of Rotterdam

3.1.2 *Overview of the findings*

The study reveals that by 2030, the vast majority of Member States plan to use only a fraction of their technical variable renewable electricity production potential. As it is shown in Figure 3-1, only 7 countries plan to use more than 10% of their technical potential for variable renewable electricity generation (the median value is 4% and the weighted average is only 6%). An opportunity is thus identified for almost all countries, as they may have enough domestic technical potential for building up additional renewable electricity capacity dedicated for hydrogen production using electrolysis.

The technical variable renewable electricity production potential can of course also be utilized for direct electricity consumption, thus avoiding the conversion losses of electrolysis.

Figure 3-1 Utilization of technical variable renewable electricity production potential by 2030

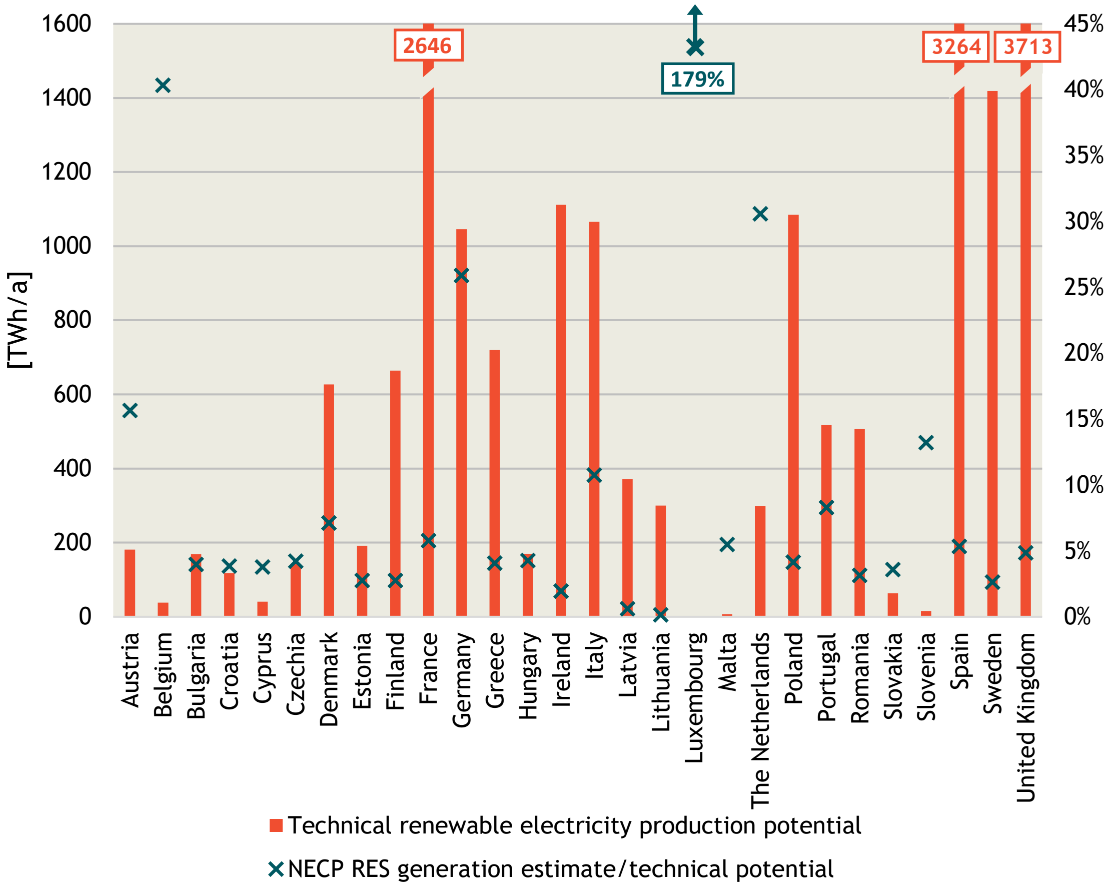
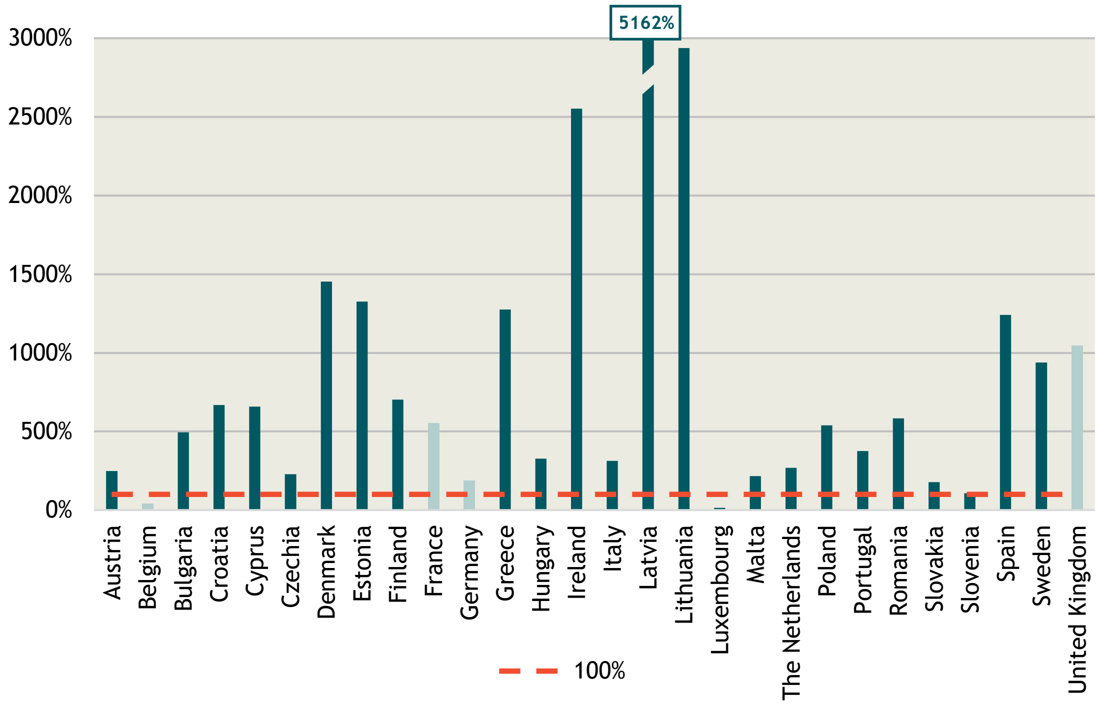


Figure 3-1 shows the ratio between the technical variable renewable electricity potential and the gross (final) electricity consumption in 2030, as forecasted in the NECPs. Only two countries (Belgium and Luxembourg) have a lower technical potential for variable renewable electricity production than their expected electricity consumption in 2030; for most other countries the technical potential is several times higher than their forecasted consumption. This suggests that the vast majority of Member States could utilize domestic renewable electricity sources for hydrogen production, even if the demand for (renewable) electricity would further increase.

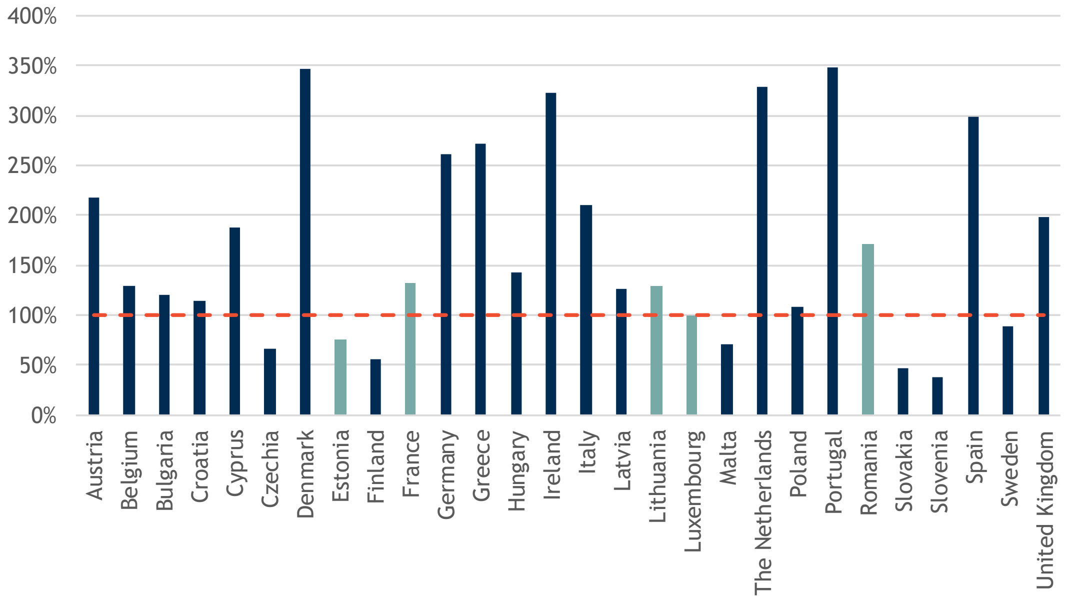
Figure 3-2 Comparison of variable renewable electricity production potential and expected electricity consumption in 2030 (NECPs / EUCO scenario)



Note: for Member States marked in light blue, the gross electricity consumption data for 2030 could not be retrieved from their NECP; in those cases, the EUCO 3232.5 scenario values were used.

Power-to-hydrogen installations can also utilize electricity from renewable electricity sources that would otherwise have to be curtailed due to insufficient electricity demand or network constraints. Figure 3-3 shows that the expected average load will in 2030 in most Member States be lower than the installed capacity of variable renewable electricity sources. Especially in countries like Denmark, Portugal, Ireland, the Netherlands and Spain, the large installed capacity of variable sources suggests that the flexibility needs will be significant, and a strong opportunity hence arises for developing hydrogen production via electrolysis to balance the electricity system. The opportunity is however limited in countries like Slovakia, Slovenia and Finland, where the installed variable renewable electricity generation capacity in 2030 is expected to be lower than the average load.

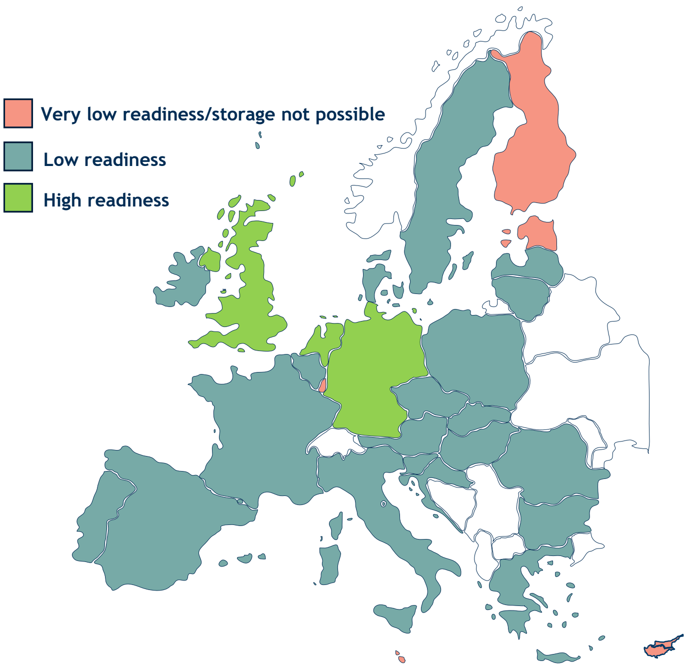
Figure 3-3 Comparison of expected average load and installed variable renewable electricity capacity in 2030



Note: for Member States marked in light blue, the gross electricity consumption data for 2030 could not be retrieved from their NECP; in those cases, the EUCO 3232.5 scenario values were used.

The readiness of Member States for deploying technologies to capture (and possibly re-use) CO_2 from hydrogen production via steam methane reforming using fossil fuels, is not specifically assessed in this study. Instead, the indicators of the Global CCS Institute were used to assess their readiness for CO_2 storage. According to this assessment, three EU countries (Germany, the Netherlands and United Kingdom) have a high readiness for CO_2 storage, and thus would have a high opportunity to produce hydrogen from fossil fuels in combination with CO_2 storage. Most Member States have a low readiness for CO_2 storage, while a few countries do not have an opportunity for developing this production pathway, since they lack suitable geographical sites for carbon storage (Estonia, Cyprus, Malta, Finland and Luxembourg).

Figure 3-4 Readiness for CO_2 storage



As most CC(U)S routes are not expected to become competitive in the 2030 time horizon, the availability of industrial by-products such as CO or CO_2 is not yet considered as a relevant opportunity or driver for hydrogen deployment, but it may become an important opportunity after 2030. There seems to be a strong industrial interest in low-carbon hydrogen and combinations with industrial by-products to produce a large variety of fuels, while lowering or capturing carbon emissions. This aspect has not been further considered in the opportunity assessment.

3.2 Potential for hydrogen transport and storage by using existing methane infrastructure

3.2.1 Context

Existing energy infrastructure is an important determinant of the extent to which hydrogen can be deployed. In this context, natural gas infrastructure is most relevant, as some of these assets can be used to transport and store hydrogen. Small volumes of hydrogen can directly be injected into the natural gas grid without adapting pipelines and end-use equipment. In the short term, this is an effective way to start the decarbonisation of the gas supply, without the need for high investments. When the produced renewable or low-carbon hydrogen volumes exceed a certain threshold, conversion of (local) pipelines to a dedicated hydrogen network may be the preferred option. Consequently, a parallel infrastructure of dedicated hydrogen pipelines and methane networks (transporting natural gas, biomethane and possibly a limited share of hydrogen) may develop. In regions with high shares of hydrogen in their energy mix, dedicated cross-border transmission pipelines for hydrogen may also be realised.

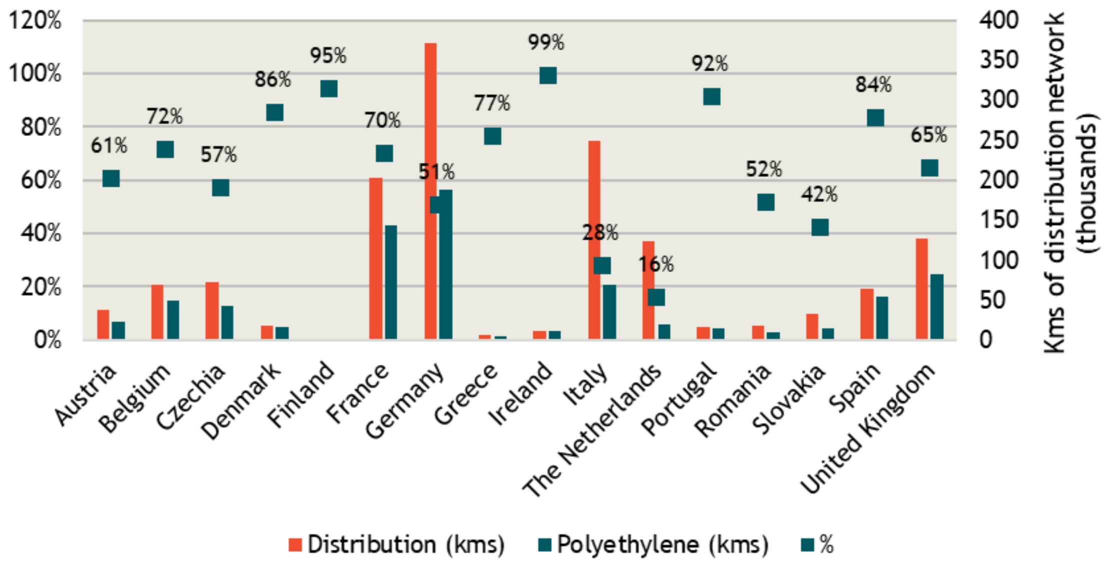
As transporting large energy volumes via hydrogen pipelines is in general less expensive than transporting the same energy volumes via the electricity grid, it might be appropriate to assess coupling large renewable power plants in remote locations (like large off-shore or onshore wind/PV parks) with electrolysers and transporting the energy output to high energy demand areas via hydrogen pipelines. This could be an opportunity to consider in several Member States.

The existence of suitable hydrogen storage infrastructure also provides an opportunity, as it enables the use of hydrogen for short-term or seasonal flexibility needs. Studies have shown that hydrogen storage is possible in salt cavern sites. Therefore, the hydrogen storage potential in this study is assessed based on existing natural gas storage sites in salt caverns on the one hand and the presence of suitable salt formations that could be used for hydrogen storage on the other hand.

3.2.2 Overview of the findings

At least half of the Member States (AT, BE, CZ, DK, FR, DE, EL, HU, IE, PT, RO, SK, ES, UK) can consider using their existing methane infrastructure for hydrogen transport and distribution, by blending hydrogen in the public grid in the short and medium term and potentially converting (part of) their network to hydrogen in the long term. As the share of polyethylene in their distribution network is in general relatively high (as illustrated in Figure 3-5), it could be converted to a dedicated hydrogen network at relatively low cost. However, conversion of the natural gas networks to a dedicated hydrogen transport system would be for most EU Member States a longer-term consideration, as the hydrogen production volumes are expected to remain relatively low until 2030 (except in a few pilot projects such as Leeds in the UK). In the short and medium term, hydrogen could hence be blended with methane in the existing grid, without the need for physical adjustments to the transport and end-use infrastructure.

Figure 3-5 Share of polyethylene pipelines in distribution system. Source: Marcogaz technical statistics (2013)



Several Member States (FR, DE, PT, RO, SK, UK) are effectively considering using their existing methane infrastructure for an admixture of hydrogen with natural gas (and biomethane). In Germany, blending hydrogen into the natural gas network is under debate.

For several Member States (BG, HR, HU, LV, LT, LU, PL, SL), there is no publicly available information regarding the share of polyethylene in their distribution network, and hence no indication regarding the technical and economic feasibility of converting the network to a dedicated system for hydrogen. These Member States could also start injecting limited hydrogen volumes into their natural gas transport and distribution infrastructure, and assess whether in the medium or long term, conversion of (part of) their methane network or construction of new dedicated pipelines for hydrogen transport and distribution would be feasible. Among the above-mentioned Member States, Hungary and Slovenia have an extensive natural gas network; they plan to carry out an assessment of their natural gas infrastructure in view of its possible use for hydrogen.

Cyprus and Malta have no potential for using existing methane infrastructure to transport or distribute hydrogen, as there is no natural gas network.

In Estonia, the methane grid has limited coverage and use intensity; the opportunity for Estonia to use this infrastructure to facilitate hydrogen deployment is therefore low. In Sweden and Finland, natural gas consumption (and related infrastructure) is also limited, but as their distribution networks are mostly made of polyethylene, they could be converted to accommodate hydrogen at a relatively low cost.

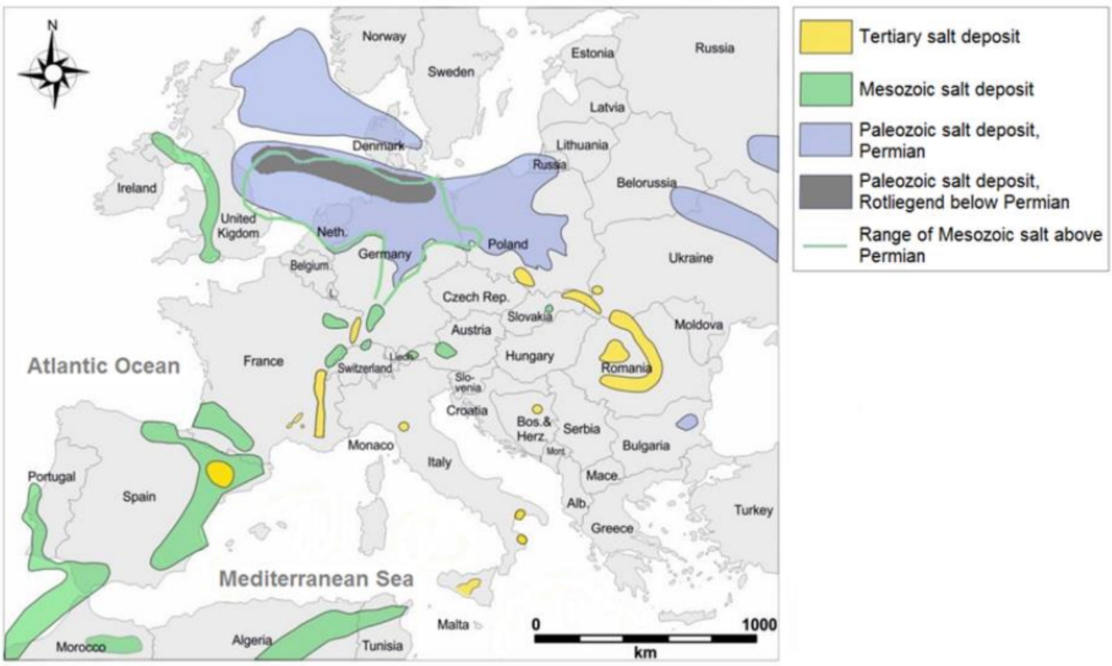
There is important existing salt cavern natural gas storage capacity in several Member States that could be used for hydrogen storage (see Figure 3-6). The availability of such suitable facilities for seasonal hydrogen storage represents an opportunity for these Member States to develop hydrogen and offers them a competitive advantage within the EU.

Figure 3-6 Existing salt cavern storage capacity. Source: Own preparation based on GIE Storage Map 2018

Source: GIE Storage Map 2018 / data as of 1 July 2018

Moreover, several Member States (AT, BG, DK, FR, IE, IT, NL, RO, SK) have underground salt layers that could provide additional hydrogen storage opportunities, as illustrated in Figure 3-7. Some of these Member States (AT, DK, RO, SK) are already exploring these possibilities and intend to undertake feasibility studies.

Figure 3-7 Potential salt cavern underground gas storage sites.



Source: Forschungszentrum Jülich (2018)

However, about half of the Member States (BE, HR, CY, CZ, EE, FI, EL, HU, LV, LT, LU, MT, SL, SE), do not have existing salt cavern methane storage facilities, nor underground salt layers that would be suitable for hydrogen storage. In Hungary, further research is currently being carried out to explore other storage possibilities, for instance to use depleted natural gas fields for hydrogen storage.

3.2.3 Main opportunities at EU level

A large majority of the Member States can consider using their existing methane infrastructure for hydrogen transport and distribution, by blending hydrogen into the public grid without the need for physical adjustments to transport and end-use infrastructure. In the medium to long term, converting (part of) their network to 100% hydrogen can be considered, and would be relatively easy, particularly in Member States where the share of polyethylene in the network is high.

Several Gas TSOs (e.g. in France, Germany, Hungary, the Netherlands) have plans to use their methane infrastructure for hydrogen transport or to set up a specific hydrogen backbone infrastructure, using existing methane pipelines for 100% hydrogen transport.

Salt caverns and underground layers are distributed across Europe and could provide a basis for a well-distributed hydrogen storage network for seasonal energy storage. Storage should also be considered when deploying transport and distribution infrastructure to link production and end-use.

3.2.4 Main barriers at EU level

The main barriers which hinder the injection of hydrogen into existing methane infrastructure and/or the conversion of existing infrastructure for dedicated hydrogen use, are:

- The lack of harmonised standards regarding the threshold content and the technical specifications to inject hydrogen within natural gas infrastructure;
- The lack of clarity regarding the options on whether hydrogen should be blended with natural gas (at least in a transitory period) or should be transported in dedicated infrastructure. This is in particular an issue if end-users require hydrogen rather than methane;
- The lack of an enabling regulation to stimulate the deployment of hydrogen applications and the use of existing methane infrastructure (e.g. certification, guarantees of origin);
- The lack of clarity regarding possible EU and national pathways that may give rise to the development of a dedicated hydrogen network and market within the EU as a basis for deploying production, transport and storage infrastructure;
- The absence of adequate EU and national frameworks for dedicated hydrogen infrastructure and markets.

3.3 Current and potential hydrogen demand

In this study, national (potential) demand for hydrogen in the EU28 is assessed independently from national potential hydrogen production, as hydrogen is expected to be produced where conditions are most favourable and be traded across the EU via existing or refurbished/new gas infrastructure. A country with a low potential for renewable electricity-based or low-carbon hydrogen could hence rely on imports from other EU Member States or non-EU countries to cover its demand. Furthermore, an EU wide hydrogen transport backbone pipeline system and market are expected to develop, allowing for the trade of renewable or low-carbon hydrogen across the EU and also import from outside the EU. Some EU Member States with high renewable energy potentials are indeed considering the development of large-scale hydrogen production for the decarbonisation of their domestic end-uses and also for the export market, while other countries are considering importing hydrogen to cover their demand.

3.3.1 Industry

In industry, three main factors were identified that strongly affect the opportunities for using renewable or low-carbon hydrogen in industry, namely:

- The level of existing hydrogen use;
- The share of natural gas in the industrial energy mix;
- The demand for high-temperature (>200°C) process heat.

The opportunities relating to the three factors mentioned above are discussed in more details in the following sections.

Decarbonising the existing use of grey hydrogen

In several industries, the use of hydrogen is well-established. Hydrogen use in ammonia production, refining, and methanol production together represent 91% of current hydrogen demand.[42] Although these sectors all use grey hydrogen, the challenges that need to be overcome in order to shift to renewable or low-carbon hydrogen differ strongly across these sectors.

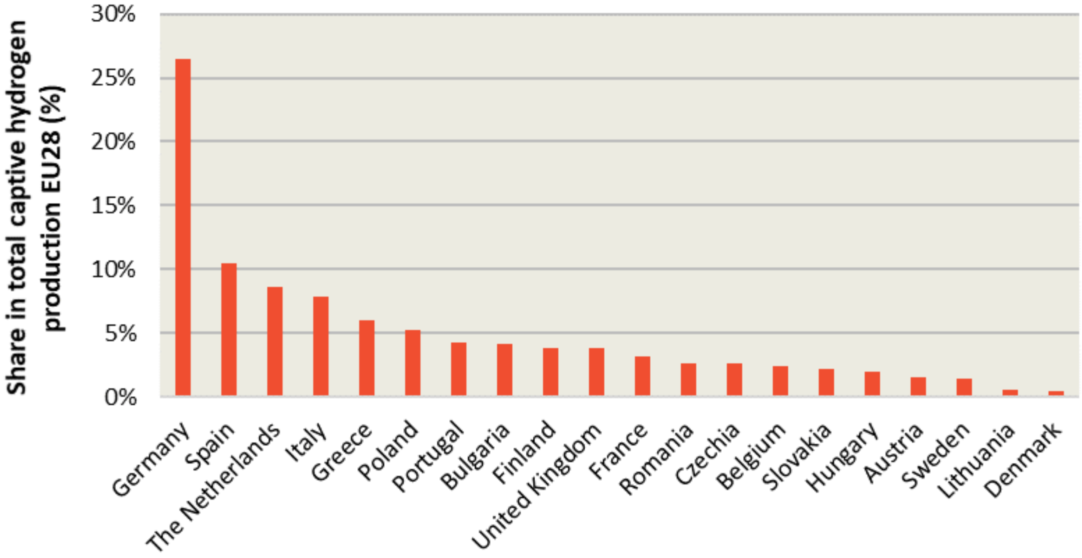
Hydrogen use in refineries

Currently, refineries are the largest consumer of hydrogen in Europe, accounting for 45% of current hydrogen demand.[43] In refineries, hydrogen is used for hydrogenation, which alters the chemical structure of the refined products being produced, and for hydro-treatment, where hydrogen is used to remove impurities such as sulphur and heavy metals from the refined products. There are currently two ways in which refineries obtain the hydrogen that is needed in their processes; hydrogen is either obtained as a by-product of specific refinery processes such as catalytic reforming or it is produced through SMR. Hydrogen represents a significant source of GHG emissions in the refining industry. In a typical refinery, SMR-related emissions account for around 8-14% of the direct GHG emissions.[44]

For refineries that are largely or fully dependent on hydrogen produced through SMR, it will be slightly more attractive to switch to renewable or low-carbon hydrogen than for refineries where hydrogen is produced as a by-product of the refining process. For this opportunity assessment, captive hydrogen production in refineries is analysed for all EU Member States (Figure 3-8). The analysis shows a large heterogeneity in the presence and size of the refinery industry across the EU and consequently in the levels of captive hydrogen demand.

[42] FCH JU (2019) Hydrogen Roadmap Europe – A sustainable pathway for the European energy transition.
[43] FCH JU (2019) Hydrogen Roadmap Europe – A sustainable pathway for the European energy transition.
[44] Amec Foster Wheeler (2017) ReCAP Project - Evaluating the cost of retrofitting CO_2 capture in an integrated oil refinery – Description of reference plants.

Figure 3-8 Indicator "presence of refining industry": share of EU MSs in total EU captive hydrogen production in refineries in 2016/2018.



Source: IHS Markit 2018, Hydrogen Analysis Resource Center - H2tools.

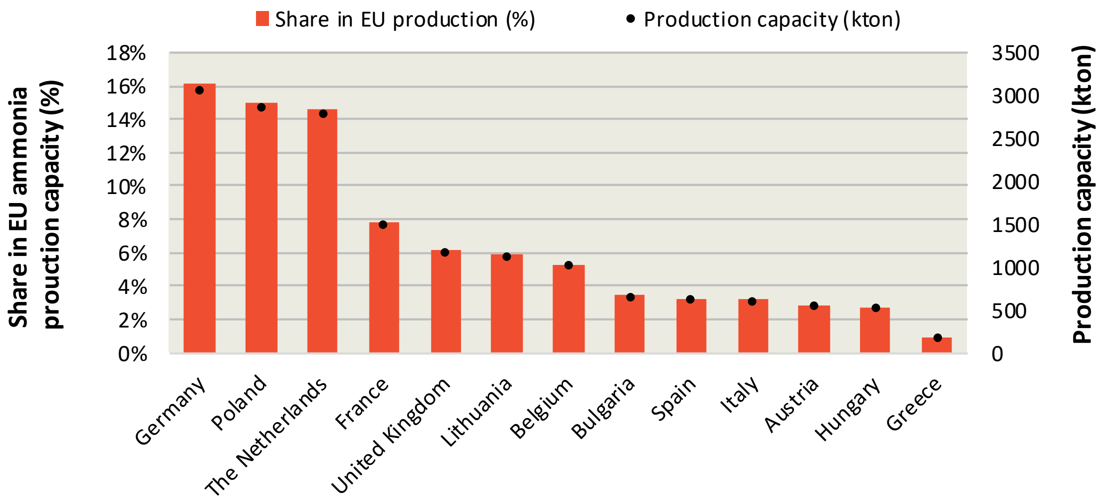
Hydrogen use in ammonia industry

The EU is an important player in the international market for ammonia and related products (e.g., urea). Most ammonia is used in fertiliser products. In ammonia synthesis, hydrogen combines with molecular nitrogen (N_2) to form ammonia. Currently, Steam Methane Reforming (SMR) where syngas is produced from natural gas accounts for most hydrogen production in Europe's ammonia industry. As the ammonia industry is only interested in the hydrogen output and not in the CO/CO_2 by-product, SMR-based hydrogen can be replaced relatively easily by renewable hydrogen production using electrolysis. Alternatively, the CO_2 produced in SMR installations can be captured, transported, and re-used in other industries or stored so that hydrogen can be produced from natural gas with a low carbon intensity. The latter would be an attractive option for ammonia producers at an ETS price of around 30 EUR/ton.[45] Renewable hydrogen production is at present still a more expensive option but is expected to become competitive with low-carbon hydrogen in the late 2020s or early 2030, depending on developments in the electricity, gas and ETS prices.[46]

In the EU, 54% of ammonia production capacity is concentrated in four countries: Germany, Poland, the Netherlands and France.[47] Overall, 12 EU Member States and the UK produce ammonia on their territory (Figure 3-9). In principle, the opportunity exists in all these countries to switch from grey hydrogen (SMR without CCS) to renewable or low-carbon hydrogen. However, in some countries the environmental factors and policy framework might be more favourable for such a shift than in others. In the Netherlands for instance, a subsidy scheme has been introduced which also allows for financial support to CCS operations, including CCS in the ammonia industry.

[45] World Energy Council – The Netherlands (2018) Hydrogen – industry as a catalyst.
[46] Ibid.
[47] Fertilisers Europe (2019) – personal communication

Figure 3-9 Indicator 'presence of ammonia industry': share of EU MSs in total EU ammonia production capacity



Source: Fertilisers Europe (2019) – personal communication.

Hydrogen use in methanol production

To date, the methanol industry is the third largest hydrogen consumer in Europe. Methanol production in Europe is highly concentrated; Germany, The Netherlands and Norway are the most important producers and some small additional plants are located in the rest of Europe (primarily in the Northwest). As in ammonia industries and refineries, SMR is the dominant technology for hydrogen production in the methanol industry. However, an important difference is that methanol synthesis does not only require hydrogen as an input, but also CO_2. This means that hydrogen production through SMR with CCS is not an appropriate option for the methanol industry and that a switch to renewable hydrogen always needs to be complemented with a 'climate-neutral' source of CO_2, such as biogenic CO_2 or CO_2 captured from the atmosphere. A switch to renewable hydrogen-based processes will hence be more costly in the methanol industry than in the ammonia industry or in refineries (that strongly depend on SMR-based hydrogen). Also, the ability to switch to such processes in the short term will depend strongly on local availability of 'climate-neutral' CO_2 sources.

The Dutch methanol producer BioMCN has done a feasibility study for installing a 20 MW electrolyser in Delfzijl, in view of expanding its methanol production capacity.[48] The CO_2 that is needed as an input would be obtained from other industrial processes nearby. The investment decision for this project is expected soon. Similarly, a consortium of 7 stakeholders agreed to build a demonstration plant for the production of methanol using renewable hydrogen, in the harbour of Antwerp.[49] This demonstration plant will be built in 2022 and will produce 8000 tonnes of renewable methanol on an annual basis.

Hydrogen use in steel industry

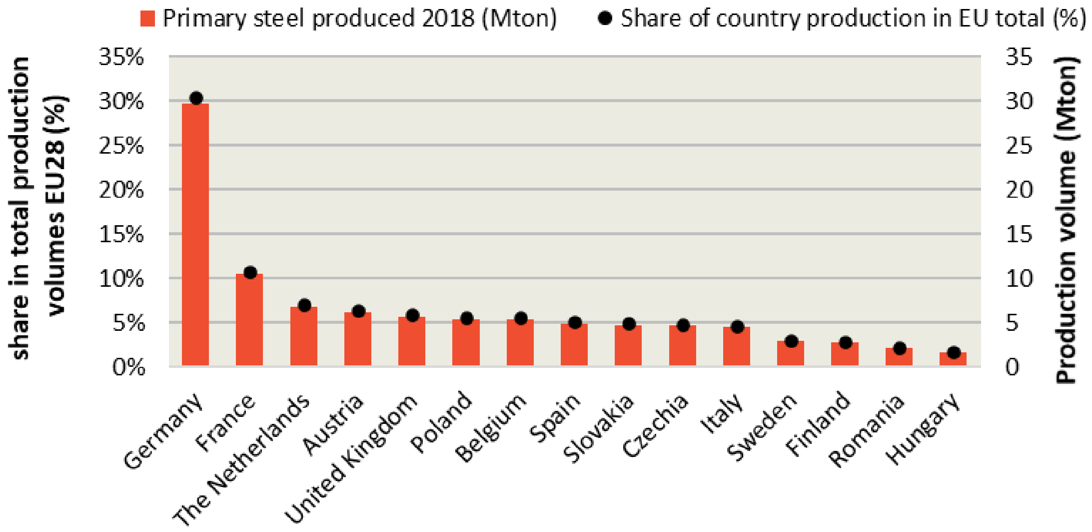
The steel industry is a carbon-intensive industry. Most plants in Europe rely on the blast-furnace/blast oxygen furnace route (BF-BOF), where coal is used as a fuel and reducing agent. There are several strategies through which GHG emissions from the steel industry can be reduced. Abatement options include the implementation of CCUS routes or deployment of the HIsarna process, which is an alternative (coal-based) direct reduction iron process. CCS has the advantage that core production processes can be retained and in HIsarna, only the blast furnace is replaced. However, these options

48 Nouryon (2019) BioMCN to produce renewable methanol with green hydrogen.
49 Port of Antwerp (2020) New milestone in sustainable methanol production in the port of Antwerp.

have the disadvantage that emissions are not fully abated, as will be required to arrive at a climate-neutral economy in 2050. An alternative is to switch to a completely different steel production process, where the BF-BOF process is replaced by a DRI-EAF process. In the first step, Direct Reduction Iron is produced using hydrogen as a reducing agent, subsequently this iron can be further processed in an Electric Arc Furnace, where it can be mixed with scrap to produce steel.

The EU accounted in 2018 for 8% of the global primary steel production and Germany is by far the largest producer accounting for 30% of EU production volume.[50] Overall, there are 13 countries in the EU that produce steel (Figure 3-10), with 7 countries that individually account for more than 5% of the production volume. In a steel market that is already coping with overcapacity, it will be challenging to shift on a large scale to a hydrogen-based production process in the short term. Still, the first small-scale pilot projects are already being started in Germany, Sweden and Austria.

Figure 3-10 Indicator 'presence of primary steel production': share of EU MSs in total EU primary steel production in 2018



Source: World Steel Association (2019) World Steel in figures 2019.

Replacing natural gas use in industry

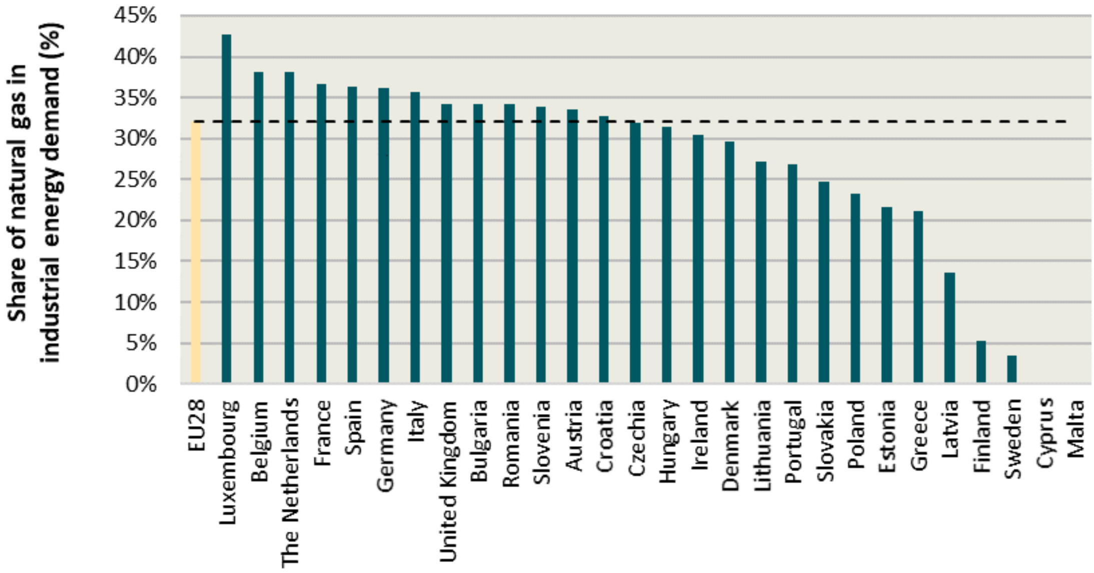
Currently, natural gas is an important fuel in European industry, accounting on average for 32% of the industry's fuel mix (Figure 3-11).[51] In 19 EU Member States, the share of natural gas in the industrial energy mix exceeds 25%. The specific focus on natural gas use in this analysis is related to the fact that natural gas can in most industrial processes be replaced relatively easily with hydrogen. In most countries with significant levels of natural gas use, natural gas is supplied via an extensive gas network. Together with biomethane, renewable and low-carbon hydrogen can be deployed to decarbonise the gas supply. When hydrogen production volumes are still relatively low, hydrogen can be mixed with natural gas in existing gas grids, without the need to invest in adjusting network components and end-use equipment. According to Marcogaz[52], major elements of natural gas transmission, storage and distribution infrastructure can indeed accept up to 10 vol.-% H2 without modification, while many industrial processes (except methane use as feedstock) are expected to be able to accept 5 vol.-% H2

[50] World Steel Association (2019) World Steel in figures 2019.
[51] Eurostat - Complete energy balances [nrg_bal_c] - Final consumption - industry sector - energy use - 2017 data.
[52] Marcogaz (2019), Overview of available test results and regulatory limits for hydrogen admission into existing natural gas infrastructure and end-use appliances

without modification. Industries that use natural gas as feedstock are sensitive to even small quantities of hydrogen and need further R&D/mitigation measures when planning to convey higher hydrogen concentrations, and thermoprocessing equipment (such as furnaces and burners) are expected to be able to accept 15 vol.-% H2 with modifications.

Some countries (like the Netherlands) are already investigating the possibility of converting (part of) their natural gas grid into dedicated hydrogen grids in the future.[53] The German gas grid operators (FNB Gas) are assessing the possibility to build a 5,900 km hydrogen grid that would be based on 90% on the existing natural gas pipeline network and could be used to transport hydrogen inside the country, while still linked to the Netherlands.[54]

Figure 3-11 Indicator 'share of natural gas in industrial energy demand in 2017'

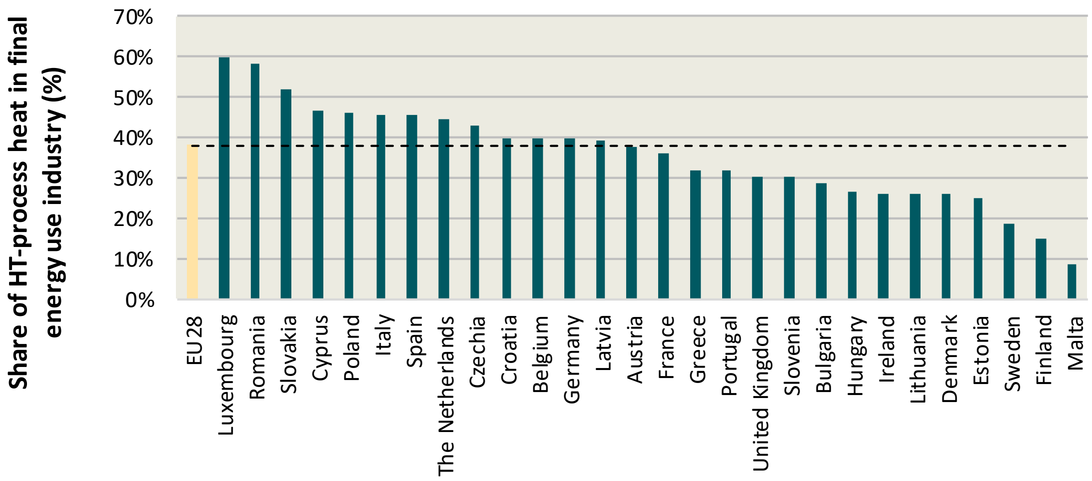


Source: Eurostat - Complete energy balances [nrg_bal_c] - Final consumption - industry sector - energy use.

A significant part of energy use in industry relates to the generation of process heat. The large share (63%) of this demand relates to high-temperature (HT) heat processes (>200°C), which hence also account for a large share of the overall energy use in industry.[55] On average 38% of industrial energy use in the EU relates to the production of high-temperature process heat, although there are strong differences across countries (Figure 3-12). Currently, this HT process heat is almost solely generated from fossil fuels, as these are energy carriers with a high energy density. There is a limited number of low-carbon options that can replace the use of fossil fuels for this purpose. For process heat up to 350-400 °C electric boilers are among available abatement technologies,[56] but for higher temperatures electrification is not an option and the only low-carbon energy carriers that remain are solid biomass, biomethane/biogas and hydrogen.

[53] Waterstof Coalitie (2018) Vier pijlers onder een duurzame waterstofeconomie in 2030.
[54] FNB (2020) Fernleitungsnetzbetreiber veröffentlichen Karte für visionäres Wasserstoffnetz (H2-Netz)
[55] Heat Roadmap EU (2017) Profile of heating and cooling demand in 2015.
[56] Berenschot. (2017). Electrification in the Dutch process industry.

Figure 3-12 Indicator 'share of high-temperature heat in industrial energy demand in 2015'



Source: Heat Roadmap EU (2017) *Profiles and Baselines for heating and cooling energy demands in 2015 for EU28 countries*

3.3.2 Transport

The transport sector is one of the most fossil fuel-dependent sectors in the EU economy and decarbonising its energy use is challenging. While overall greenhouse gas emissions in the EU declined by 22% between 1990 and 2017, emissions from the transport sector increased over the same period by 28% and are expected to increase further. Next to the use of renewable and low-carbon fuels including hydrogen, a shift to smarter and more integrated mobility is needed. Implementation of EU regulation will support this transition, particularly the EU Directive on alternative fuels infrastructure (Directive 2014/94/EU) and new CO_2 emission performance standards for passenger cars and heavy-duty vehicles.

To reach required emission reductions in the transport sector, a switch to renewable or low-carbon energy carriers is essential. Hydrogen can play a key role in this domain, either via the direct use of hydrogen in fuel cell-powered cars, trucks, buses, trains and ships, or via the production of hydrogen-based synthetic liquid fuels for the shipping and aviation sectors.

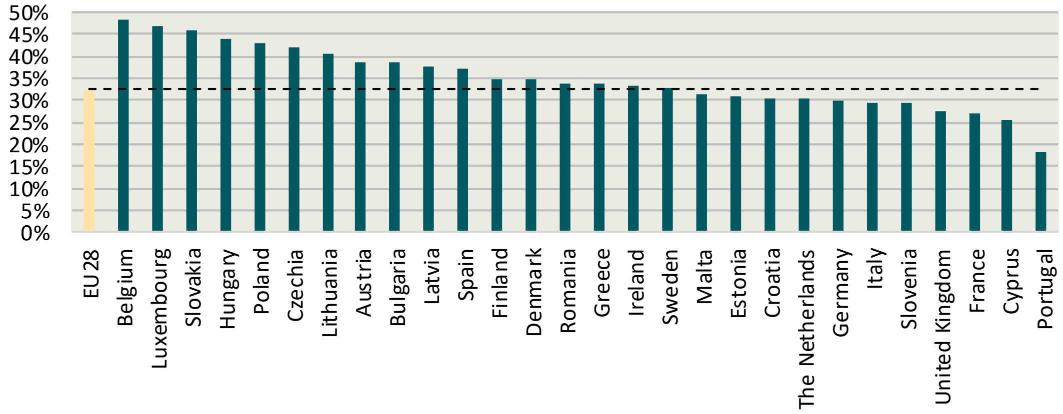
Road transport

The road transport sector today is still heavily dependent on the use of fossil fuels, which account for 95% of energy demand in the sector. In road transport, variation between Member States in terms of energy mix is relatively limited (Figure 3-14). Fossil fuel shares in road transport are substantially lower than the EU average only in Sweden, which is mainly due to the use of biogas for transport in some of Sweden's urban areas.

When looking at the future, electrification is expected to make a large contribution to the decarbonisation of the passenger car segment. Still, fuel cell electric vehicles (FCEVs) which use hydrogen as a fuel could complement battery electric vehicles (BEVs), as they have the advantage of larger driving ranges. Due to their higher energy storage density compared to BEVs, FCEVs are also an attractive option for larger cars in this market segment.

Apart from passenger cars, around one third of the energy in road transport in the EU28 is consumed by vans, buses and trucks (Figure 3-14). In this market segment, FCEVs are an attractive vehicle type to replace the existing diesel vehicles.[57] For short distances, BEVs are an alternative.

Figure 3-13 Share of heavy-duty road transport in total final energy demand road transport in 2017.

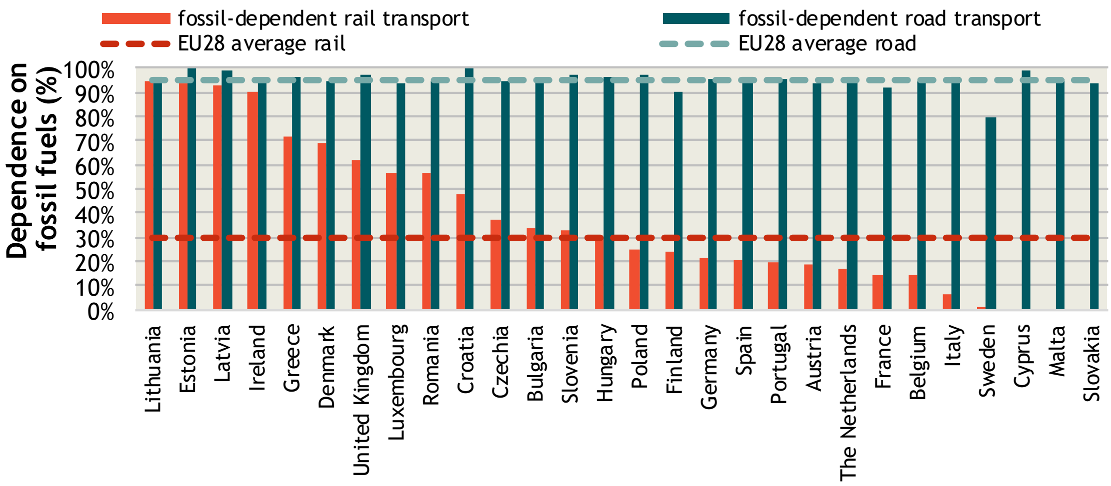


Source: PRIMES (2016) EU Reference Scenario 2016 - Energy, transport and GHG emissions - trends to 2050.

Rail transport

In rail transport, there is a large variation in the fuel mix across EU Member States (Figure 3-14). On average, dependence on fossil fuels in the sector is 30% at the EU28 level. However, in some countries, like the Baltic states and Ireland, over 90% of the energy mix in rail transport is still based on fossil fuels. In most Member States a large part of the railway system is electrified. Further electrification is therefore one of the logical ways forward for the decarbonisation of this sector. However, depending on local conditions, Fuel Cell trains can be a more attractive and, in some cases, less expensive option than electrification. Fuel cell trains have the advantage that they can be operated for a long time (over 18h) without refuelling, after which refuelling can be done quickly.[58] A recent study shows that by 2030, already 30% of the diesel trains currently in operation can be replaced by fuel cell trains.[59]

Figure 3-14 Indicators on fossil fuel share in final energy demand road and rail transport in 2017.



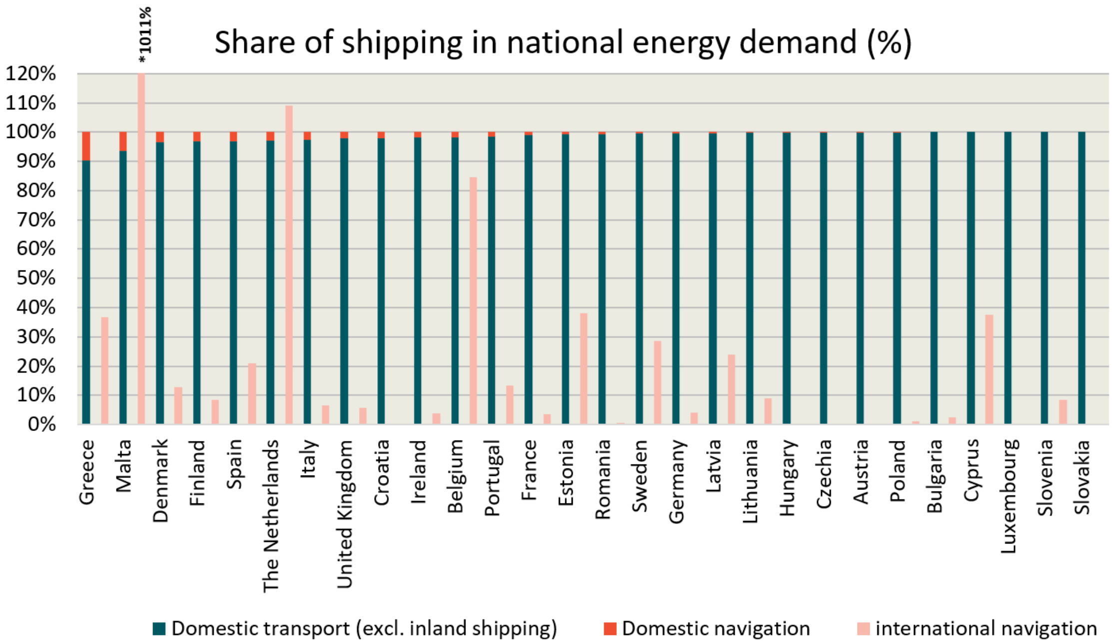
Source: Eurostat - Complete energy balances - Final energy demand in road transport and rail transport by fuel

[57] Hinicio & LBST (2018) Techno-economic & environmental performance comparison of GHG-neutral fuels and drivetrains for heavy-duty trucks.
[58] Roland Berger (2019) Study on the use of fuel cells and hydrogen in the railway environment.
[59] Ibid.

Decarbonisation of the shipping sector

In most countries domestic shipping represents a relatively minor share of energy use in transport (Figure 3-15). In 2017, there were only two Member states where the share of this sector in the total energy use in transport exceeded 5%. However, the sector is strongly dependent on fossil fuels, with smaller ships mostly running on diesel fuels and larger ones on fuel oil.

Figure 3-15 Share of inland shipping in final energy demand & energy demand for international shipping relative to energy demand for domestic transport 2017.



** The bar for Malta goes off the chart as the energy use for international shipping in Malta is more than 10 times larger than the energy demand for domestic transport.*
Source: Eurostat - Complete energy balances - Final energy demand for inland navigation, energy use for international maritime bunkering, and total final energy consumption in transport.

The international shipping sector is a more significant energy consumer. Although energy use for international shipping is not included in the transport energy use of a country, the equivalent of 14% of the total domestic energy use in transport in the EU28 was used to fuel international ships. In countries with large harbours, such as the Netherlands and Belgium, the energy use for international shipping can be very substantial (Figure 3-11). In the Netherlands, the total energy use for bunkering international ships is 9% larger than the entire domestic energy demand for transport, and in Belgium the consumption of fuels for bunkering ships is equivalent to 85% of its domestic energy use in transport. Island states and countries with large archipelagos such as Greece, also have substantial energy consumption levels for international shipping. In Malta, the energy consumption for international shipping is even more than 10 times higher than its domestic energy use in transport.

The international shipping sector does not fall under national climate mitigation policies. The International Maritime Organisation has announced its ambition to reduce annual greenhouse gas emissions by at least 50% by 2050,[60] but this is not sufficient in view of the objective to stay well-below 2°C of global warming as agreed in the Paris Climate Agreement.[61]

[60] IMO - Reducing greenhouse gas emissions from ships.
[61] Halim et al. (2018). Decarbonization Pathways for International Maritime Transport: A Model-Based Policy Impact Assessment.

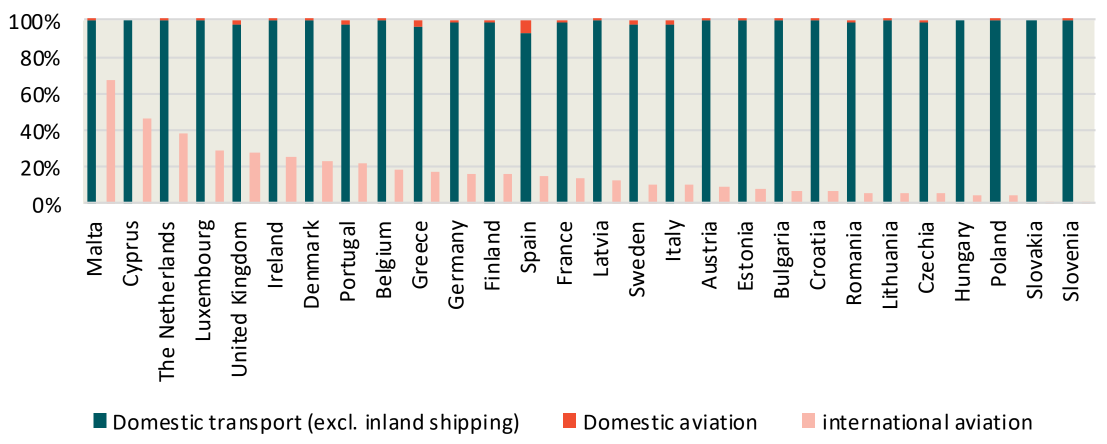
The number of decarbonisation options available to the shipping sector is rather limited. For smaller ships used for domestic navigation, electrification can be an option. However, the largest part of the shipping sector will be dependent on low-carbon liquid fuels, including biofuels (e.g. advanced biodiesel), hydrogen and derived fuels. In the medium term, between now and 2040 liquefied natural gas is expected to play a significant role as well, followed by a gradual phase out of this technology after 2040.[62] When looking at hydrogen related technologies, it is not completely clear yet which technologies are most suitable from a technical and economic perspective. Options being investigated include liquefied hydrogen, ammonia, methanol and synthetic methane, which can be compressed to obtain liquefied natural gas and potentially synthetic liquid fuels, e.g. synthetic diesel.[63]

The role of hydrogen in aviation

As with the international shipping sector, international aviation does not fall under national climate agreements. The international aviation organisation IATA has stated the ambition to reduce its GHG emissions by 50% compared to 2005 levels by 2050.[64] International aviation accounts for 89% of the total energy use in the aviation sector, with the remainder attributable to domestic flights (which are covered by national climate policies).

In the aviation sector, the options for decarbonisation are even more limited than in the shipping sector. For very small-size city hoppers, electrification is possible, but for larger airplanes flying longer distances electrification is not an option. For this segment, liquid biofuels and synthetic fuels produced from hydrogen seem to be the most suitable low-carbon fuels.[65] The airline company Lufthansa has recently announced that it will start using synthetic fuels to cover 5% of its operations at Hamburg airport.[66] In the long term, direct use of hydrogen in airplanes either through combustion in a jet engine or in fuel cells to power an electric propulsion system might also become an option.[67] It is expected that these options will be most suitable for the narrow-body/middle-of-the airplane market segment.

Figure 3-16 Share of domestic aviation in final energy demand & energy demand for international aviation compared to energy demand for domestic transport 2017.



Source: Eurostat - Complete energy balances - Final energy demand for domestic aviation, energy use for international aviation, and total final energy consumption in transport.

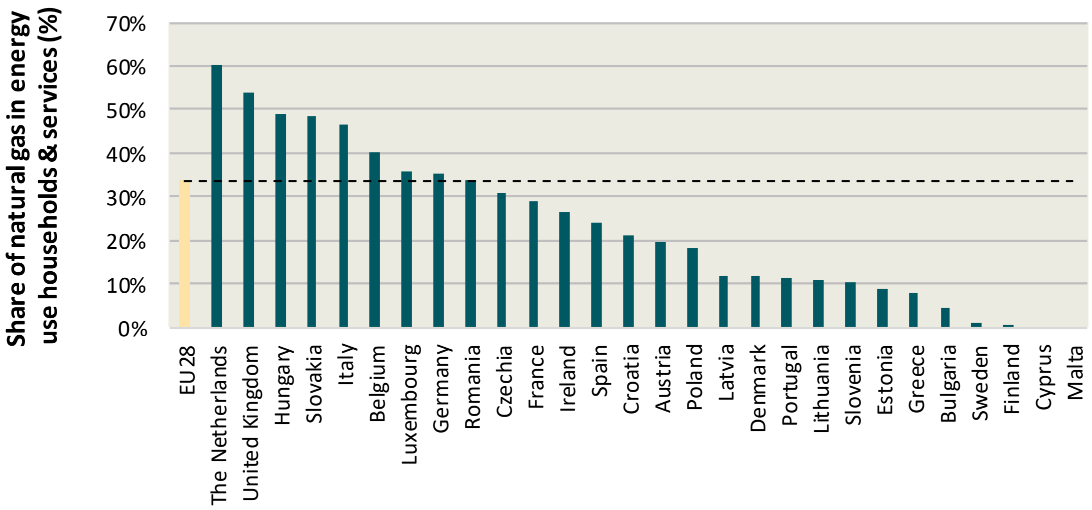
[62] DNV-GL (2019a). Forecasting the effects of world fleet decarbonisation options.
[63] Transport & Environment (2018a). Roadmap to decarbonising European Shipping; DNV-GL (2019b) Comparison of Alternative Marine Fuels.
[64] IATA (2018). Fact Sheet - Climate Change and CORSIA.
[65] Transport & Environment (2018b). Roadmap to decarbonising European aviation.
[66] Transport & Environment (2019). Lufthansa takes first steps towards non-fossil kerosene.
[67] Roland Berger (2020). Hydrogen - a future fuel for aviation?

3.3.3 Heating and cooling in the built environment

In the EU, about 27% of final energy demand is used for heating buildings. In most countries, heating of buildings still strongly depends on fossil fuels. While electric heat pumps provide a suitable and energy efficient solution for well-insulated buildings, their use in older building stock is challenging. Especially in regions where a large share of buildings is connected to a district heating grid or to a natural gas distribution grid, renewable or low-carbon hydrogen can contribute to decarbonising household energy use.

To date, natural gas is an important fuel for heating in the built environment in the EU. In 2017, natural gas accounted on average for 34% of the final energy demand in the residential and services sectors combined. This natural gas is primarily used for space heating, followed by water heating and cooking. Renewable and low-carbon hydrogen could be an attractive option for the decarbonisation of neighbourhoods connected to the gas grid, where building stock is old and investments in upgrades of existing buildings are difficult or very costly. As explained in the section on industry, hydrogen can be transported to end-users in the built environment through the blending of hydrogen with natural gas in existing gas grids. Alternatively, when the local availability of/ demand for hydrogen is large enough, existing natural gas grids can be converted to dedicated hydrogen grids. Potentially, the suitability of this option can be evaluated at the level of individual distribution networks. In this way a meshwork of natural gas grids (potentially with H2 blended in) and dedicated hydrogen grids could develop.

Figure 3-17 Indicator 'share of natural gas in final energy demand services and households in 2017'



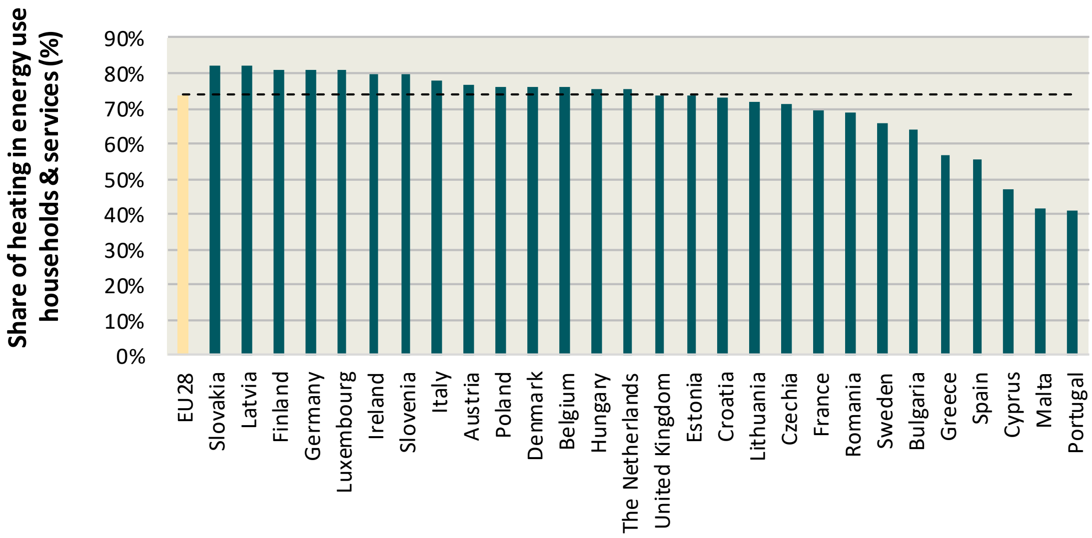
Source: Eurostat - Complete energy balances - Final energy consumption in households and services sector.

The demand for heating varies substantially across Member States, mainly due to climatic differences. On average, the need for heating accounts for 74% of the final energy demand in the built environment,[68] with Slovakia (82%) and Latvia (82%) exhibiting the highest shares, and Malta and Portugal exhibiting the lowest shares: 42% and 41% respectively. In countries where the demand for heating coincides with high shares of direct or indirect use of fossil fuels to supply the heat, hydrogen could be deployed as one of the decarbonisation options. Hydrogen boilers or hydrogen based micro-

[68] Fraunhofer ISI (2017). Profile of heating and cooling demand in 2015.

CHP installations could replace existing fossil fuel-fired heating equipment on-site, or hydrogen can replace fossil fuel use at district heating plants, which are also common in several Member States.
In summary, the opportunities for hydrogen use in the built environment were identified to be relatively large in northwest and central Europe, where fossil fuel shares in the heating mix are relatively high. In Southern Europe, the overall demand for heating is lower, but fossil fuels are still a dominant source for heat production in many of these countries including Italy and Spain, where fossil fuels account for 68 % and 66% of the energy mix for heating, respectively. The potential for the use of hydrogen in heating applications seems to be most limited in the Baltics, Finland and Sweden, due to high shares of biomass in the energy mix, and in some countries in Southern Europe with low heating demand and relatively lower levels of fossil fuel use.

Figure 3-18 Indicator 'share of heating in final energy demand services and households in 2015'

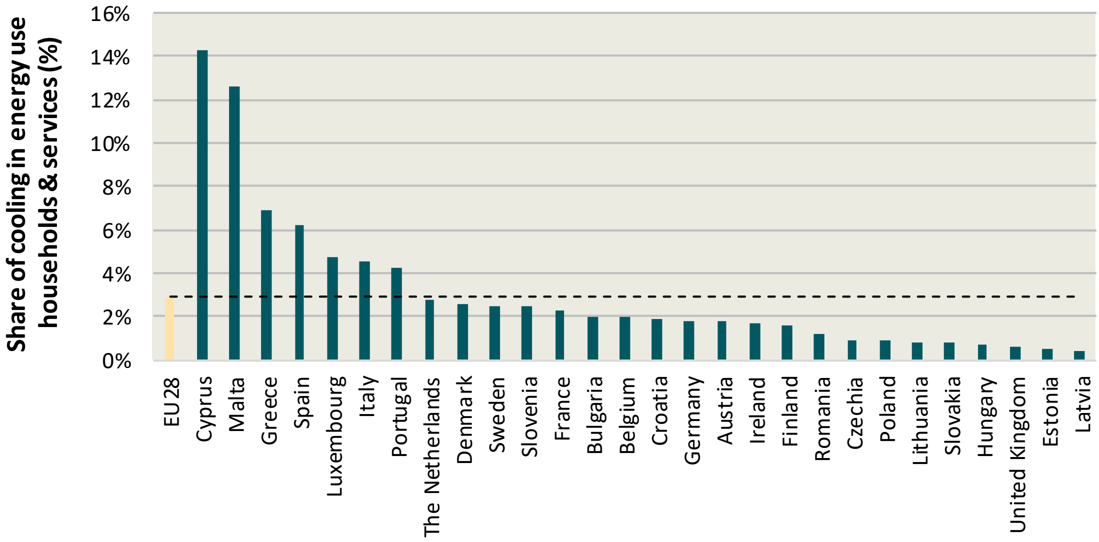


Source: Fraunhofer ISI (2017) Profile of heating and cooling demand in 2015.

The role of hydrogen in cooling

In addition to energy demand for heating, some countries have a substantial energy demand for cooling. Overall, the energy demand related to cooling is much lower than the demand for heating, but in the face of climate change demand for cooling is expected to grow. Currently, electric air conditioners satisfy the largest part of the cooling demand. There are some gas-based air conditioners and reversible heat pumps in the market, but their market share is still very low. In the future, some of these gas-based cooling systems could switch from natural gas to hydrogen, but it should be noted that such technologies are still at a low TRL level and are not expected to be deployed on a significant scale in the period up to 2030.

Figure 3-19 Indicator 'share of cooling in final energy demand services and households in 2015'



Source: Fraunhofer ISI (2017) Profile of heating and cooling demand in 2015.

3.4 Enabling political and industrial environment for hydrogen development

3.4.1 Context

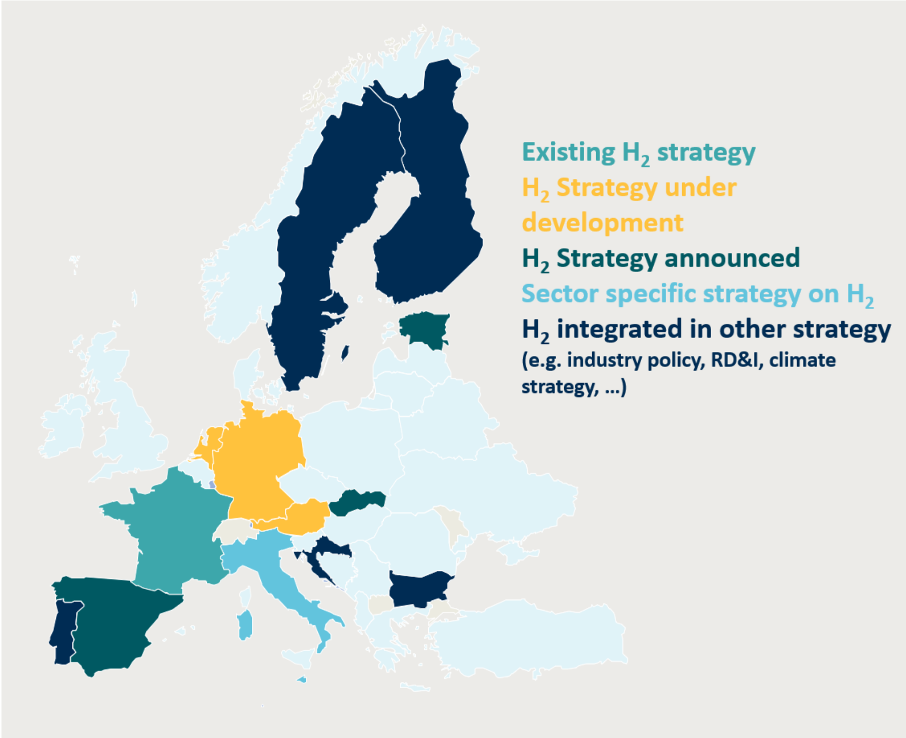
Next to the physical and energy system characteristics, there are also political, social, and industrial factors that influence national potential for hydrogen development. The presence of research institutes or private companies that are active in hydrogen-related activities can, for example, act as a driver of hydrogen development. Also, a stimulatory policy framework that includes policies or roadmaps aimed at hydrogen production or the roll-out of hydrogen refuelling infrastructure and end use applications can positively contribute to hydrogen deployment. Lastly, there are political factors that can indirectly stimulate local renewable or low-carbon hydrogen deployment, such as high energy import dependence or carbon pricing policies (beyond the EU ETS).

3.4.2 Overview of the findings

National hydrogen roadmap or strategy

Member States have adopted different approaches to address the potential and challenges of hydrogen deployment through national hydrogen roadmaps and strategies, by integrating hydrogen in other policies (e.g. industrial policy), through sector specific hydrogen strategies, and through hydrogen RD&I programmes (as developed in section 2.1.4 and illustrated in Figure 3-20). In the opportunity assessment, the existence of a specific national roadmap or strategy is considered an enabler for hydrogen deployment in the concerned Member State.

Figure 3-20 Strategies and roadmaps related to hydrogen development, next to the NECPs



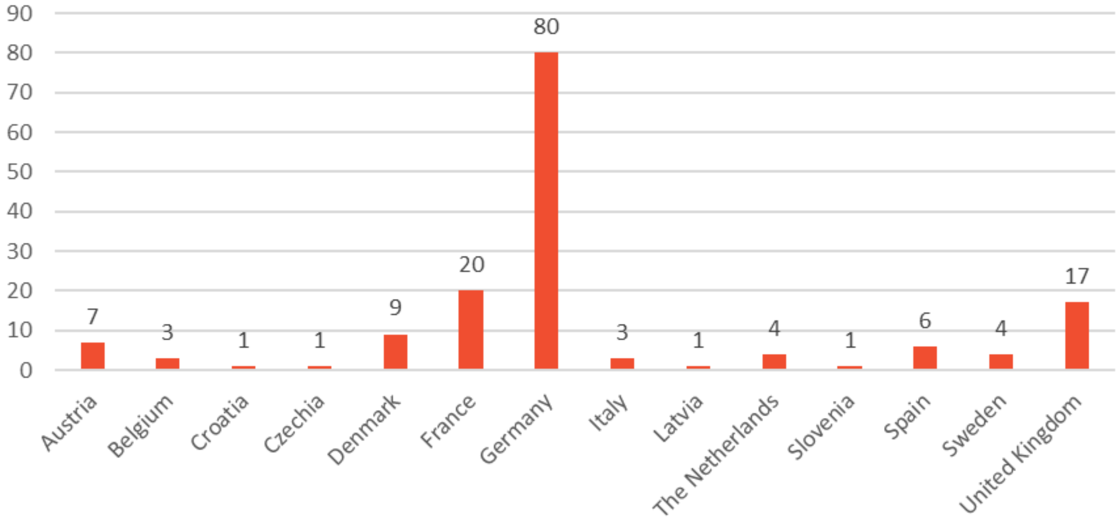
Hydrogen deployment in the context of the Alternative fuels infrastructure Directive

In their National Policy Frameworks (NPFs), submitted in November 2016 in the context of the Alternative fuels infrastructure directive (2014/94/EU), fewer than half of the Member States have already included measures or targets regarding development of hydrogen infrastructure for the transport sector. Where Member States do show an early interest in hydrogen, it is considered an enabling factor for further development. The recently submitted NECPs provide updated information regarding national targets and measures for this specific end-use sector.

Hydrogen related research and industrial projects

Thanks to European and national co-funding via generic or dedicated programmes, research institutes and industry are in most EU Member States active in different hydrogen domains: research, demonstration and pilot projects for hydrogen production (e.g. electrolysers), hydrogen filling station infrastructure, projects related to hydrogen transport and storage (including refurbishment of methane infrastructure, end-use equipment). More details about the different projects are provided in the Member States' fiches. The number of hydrogen refuelling stations per Member State by mid-2019 is presented in Figure 3-21.

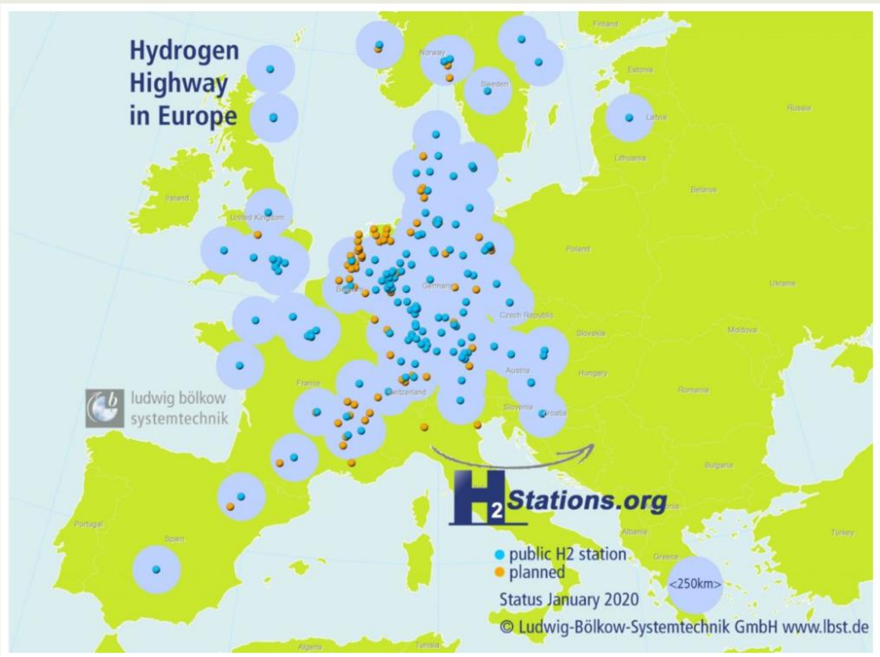
Figure 3-21 Number of hydrogen refuelling stations per Member States by mid-2019 (source: LBTS HRS database)



The following Box 3-2 provides more up to date data regarding the deployment of hydrogen refuelling stations throughout Europe.

Box 3-2 FuelCellWorks - Hydrogen Refuelling Stations in Europe[69]

With 36 new hydrogen stations opened in 2019, Europe had 177 hydrogen stations at the end of the year, 87 of which are in Germany. France is second in Europe with 26 operating stations and 34 planned hydrogen stations with further dynamic expansion expected. However, while the rest of Europe focuses on publicly accessible car refuelling stations, most of the French stations aim at the refuelling of buses and delivery vehicle fleets. Stations are projected to significantly increase in the Netherlands, where 21 new hydrogen refuelling stations are being planned.



Source: https://fuelcellsworks.com/news/in-2019-83-new-hydrogen-refuelling-stations-worldwide/

[69] https://fuelcellsworks.com/news/in-2019-83-new-hydrogen-refuelling-stations-worldwide/

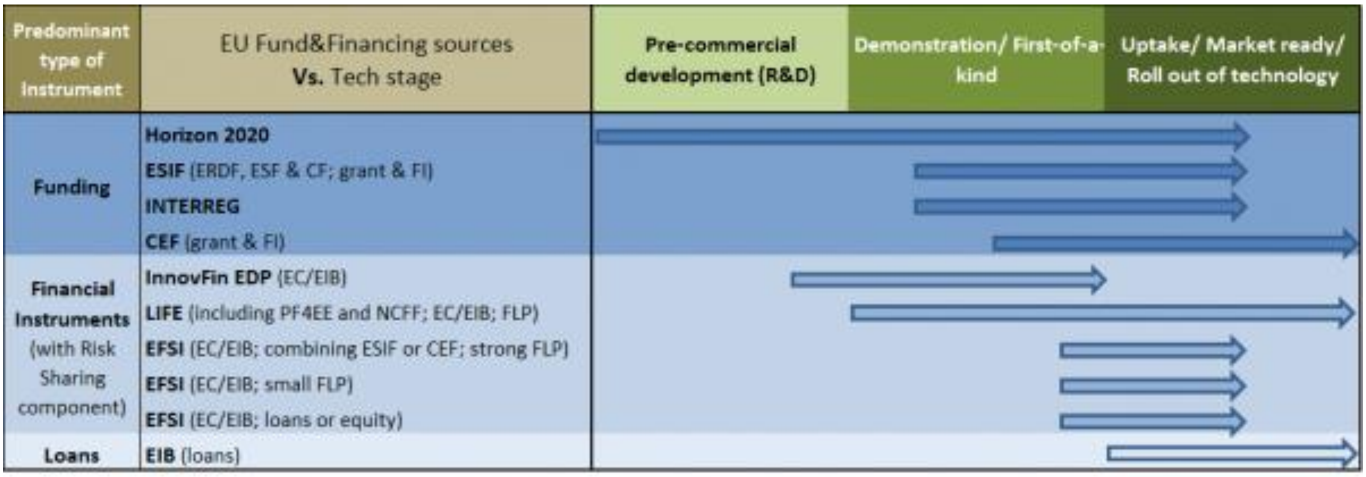
Several Member States are involved in potential **Important Projects of Common European Interest** (IPCEIs)[70]. This instrument aims to contribute to the European Union's objectives, involve multiple Member States, and have positive spill-over economic or social effects. Requiring co-financing by the beneficiary of EU's financial assistance, the IPCEIs may be R&I or first market deployment projects with a high innovation or value-added component to the supply chain.

In view of identifying potential IPCEIs on hydrogen, a conference in late 2019 aimed to launch a platform to identify the most promising projects and increase collaboration between industry and public actors for hydrogen IPCEIs.[71] Projects presented in the conference address hydrogen transport through pipelines and other means, as well as other parts of the value chain:

- A hydrogen backbone in France, Belgium, Netherlands, Germany integrating hydrogen supply and demand, facilitated by ports and industrial clusters;
- Heavy duty road transport with hydrogen trucks;
- Last-mile distribution with hydrogen vehicles;
- Large-scale hydrogen production from renewable off-grid and fluvial transport to demand centres;
- Hydrogen for passenger and cargo ships propulsion and power systems;
- Cargo ships for liquid hydrogen;
- Large-scale manufacturing for solar PV and water electrolysis technologies;
- Large-scale hydrogen production and distribution in ES and central Europe;
- Substitute lignite by solar PV and reversible fuel cells.

At EU level, several **funding instruments** are available to accelerate the market introduction and deployment of innovative energy technologies, including hydrogen. The following instruments support hydrogen projects at different stages of technology readiness:

Figure 3-22 EU funds & financing sources

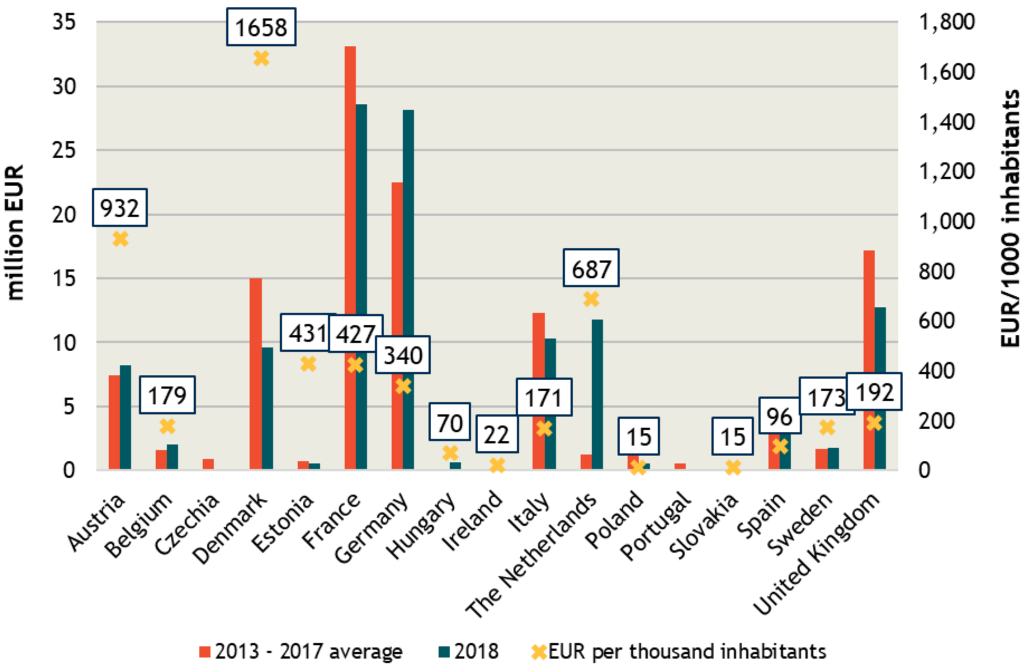


Source: Adapted from https://www.fch.europa.eu/page/combining-funds

Most Member States are actively engaged in hydrogen related RD&I activities. The average budget levels spent in 2013-2017 are presented in Figure 3-23 (data are only available for 17 countries). The figures for 2018 are also added.

[70] IPCEI projects: https://www.hydrogen4climateaction.eu/projects
[71] See https://www.hydrogen4climateaction.eu/

Figure 3-23 National RD&I expenditure on hydrogen & fuel cells. Average annual budget 2013-2017 in million EUR, the 2018 budget and the 2018 budget relative to the number of inhabitants[72]



Hydrogen in the investment plans of the natural gas TSOs

During the development of the TYNDP 2020 for gas, ENTSOG acknowledged the need to go beyond standard methane transmission, storage and LNG terminal projects when planning natural gas system development. A new category of "Energy Transition Related" (ETR) projects was added, including power-to-gas and CCU/S facilities. Among the 41 ETR projects submitted for assessment, there are some projects dedicated to hydrogen-related infrastructure as shown in Table 3-1, in particular[73]:

- Power-to-gas facilities for hydrogen production;
- Methanation facilities to convert hydrogen to synthetic methane;
- Conversion of existing natural gas pipelines for transport of hydrogen, or build-up of new hydrogen dedicated transport pipelines;
- Projects focusing on mixing hydrogen into natural gas networks.

Table 3-1 Hydrogen ETR candidate projects in the ENTSOG TYNDP 2020

Project Name	Developer
Hub Aragon	Enagas
Hub Baleares	
Hub Murcia	
Hub País Vasco	
Sun2Hy	
HyOffWind Zeebrugge	Fluxys, Eoly, Parkwind
North Sea Wind Power Hub	Gasunie
Renewable Hydrogen according to NEP2020	Gasunie Deutschland
Jupiter 1000	GRTgaz, Terega
PtG Production with infrastructure building/enhancement	JSC "Conexus Baltic Grid"

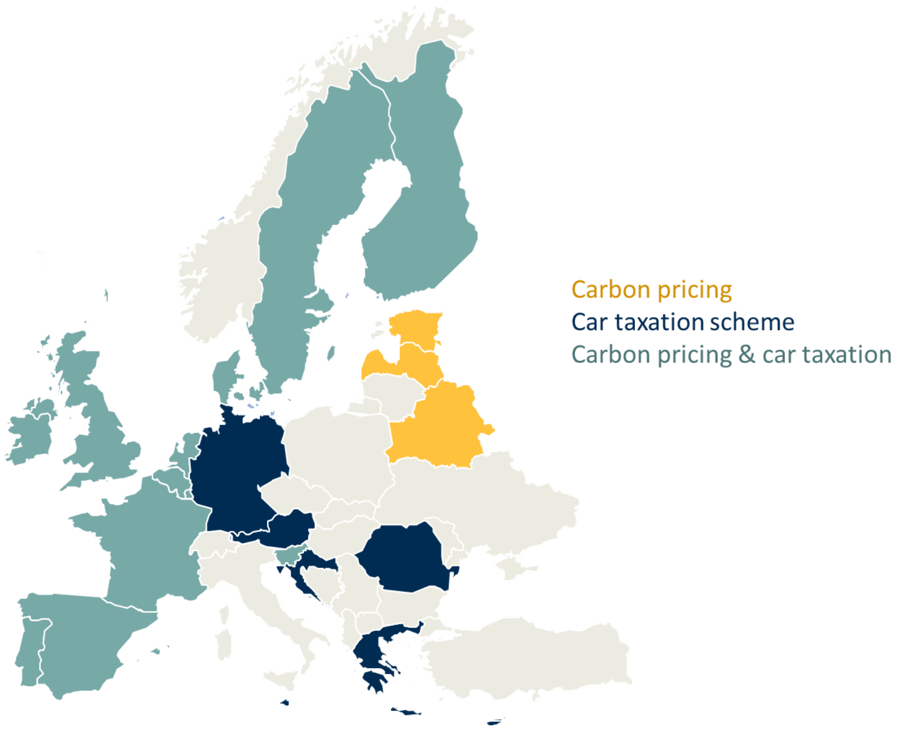
[72] IEA, RD&D budget expenditure database
[73] ENTSOG (2019), ENTSOG Ten Year Development Plan.

Project Name	Developer
G2F - Gas to Future	NAFTA
Hydrogen transmission backbone Netherlands	Nederlandse Gasunie
Greening of Gas (GoG)	NET4GAS
Djewels	Nouryon
GETH2-ETR 1	Nowega
Hydrogen Region Lausitz	ONTRAS
Energy Park Bad Lauchstädt	
hybridge - gas grid infrastructure	Open Grid Europe
P2G integrated in transmission grid	Reganosa
PEGASUS	S.G.I.
Power-to-gas plant in the south of Italy	Snam Rete Gas
Transport of hydrogen via natural gas network	
Impulse 2025	Teréga
Element Eins	Thyssengas, Gasunie Deutschland, Tennet

Existence of national financial or fiscal incentives (CO_2 pricing mechanisms & car taxation)

Several Member States have adopted financial or tax schemes to stimulate the procurement of low-carbon vehicles (e.g. emissions-related registration tax, grants). Some Member States have adopted carbon pricing to incentivise the use of low carbon fuels, while others adopted both schemes, as illustrated in Figure 3-24 (based on the information available in the NECPs).

Figure 3-24 Carbon pricing and car taxation schemes



Hydrogen deployment as opportunity to reduce fossil energy import dependence and bill

Most EU Member States strongly depend on imports for their natural gas as well as oil consumption. Switching from fossil fuels to nationally produced hydrogen for industrial processes and heating applications and promoting the use of hydrogen in the transport sector would contribute to reducing their import dependence and bill.

The presence of domestic fossil fuel reserves can act as a barrier or an opportunity for the deployment of H_2 technologies, depending on national context. On one hand, there is an economic incentive to extract fossil resources in order to utilise their economic value, which acts as a barrier for the deployment of renewable hydrogen; on the other hand, the presence of a strong fossil energy sector with the appropriate know-how can act as a driver for production of low-carbon H_2 and the development of a hydrogen-based system.

Public acceptance is key to facilitating hydrogen infrastructure and use

Lack of public acceptance regarding energy infrastructure development in general and hydrogen infrastructure in particular can act as a barrier to the development of dedicated hydrogen storage capacities and transport or distribution infrastructure. Public and consumer acceptance can crucially influence the deployment of large-scale hydrogen projects (including hydrogen storage) as well as the adoption of hydrogen and fuel cell applications in the buildings and transport sector.[74,75] Given that public preferences may hinder hydrogen development, understanding attitudes and behaviours (and how to influence these) is key. However, there is at present limited specific information and understanding of these issues at EU level. Two key projects have conducted some preliminary work regarding public perception of hydrogen (Hyacynth and HyUnder), though in a limited geographical scope.[76]

The **Hyacinth project**[77] focused on this issue and found that in 2014 only 6% of surveyed stakeholders were familiar with hydrogen and fuel cell technologies.[78] The Hyacinth project provides a toolbox and recommendations for policy makers and hydrogen and fuel cell developers to improve public engagement.[79]

The **HyUnder project** explored lay people's beliefs, ideas and evaluations of hydrogen storage and associated concepts. The project highlighted that many factors influence perception of project plans, including for example, local demographics, earlier experienced risks, trust in the local, regional, and national government as well as trust in project developers, awareness, knowledge and perceptions of energy options, among others.[80] According to the findings of this study, opposition to projects is often tied to project approaches themselves. Each project is unique and, as such, management of public participation and communication processes is only effective if tailored to the specific context.

[74] Hyacinth project (2014a), Hydrogen acceptance in the transition phase. Deliverable 5.2 – General findings on public acceptance.
[75] HyUnder (2013), Assessment of the potential, the actors and relevant business cases for large scale and seasonal storage of renewable electricity by hydrogen underground storage in Europe.
[76] Hyacinth focused on Belgium, France, Germany, Norway, Spain, Slovenia, and United Kingdom; while HyUnder focused on the Netherlands.
[77] Hyacinth project aimed to assess levels of awareness, understanding and acceptance of FCH technologies in the general public in various EU countries with different levels of market penetration and government support. Specifically, the project has aimed at examining public attitudes towards residential fuel cell units and hydrogen fuel cell electric vehicles in Belgium, France, Germany, Norway, Spain, Slovenia, and United Kingdom. More information available in the project's website: http://hyacinthproject.eu/
[78] Hyacinth project (2014a), Hydrogen acceptance in the transition phase. Deliverable 5.2 – General findings on public acceptance.
[79] Hyacinth project (2014b), Hydrogen acceptance in the transition phase. Deliverable 6.5 – Social awareness report.
[80] HyUnder (2013), Assessment of the potential, the actors and relevant business cases for large scale and seasonal storage of renewable electricity by hydrogen underground storage in Europe.

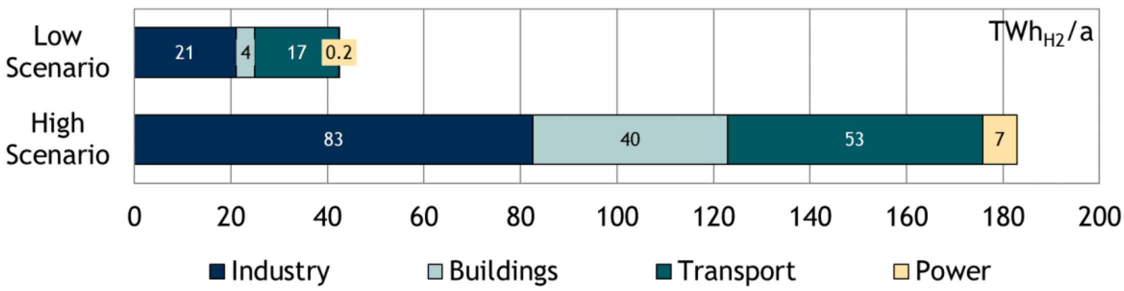
4 Assessment of hydrogen deployment in the high and low scenario

The evaluation of the impacts of hydrogen deployment presented in this chapter is conducted for a low and a high scenario covering the range of uncertainty. It starts in section 4.1 with an estimation of the expected hydrogen demand by 2030 in different sectors and sub-sectors in the two scenarios as a basis for further analyses. It is followed in section 4.2 by the sizing of the corresponding hydrogen-related technologies such as electrolysis capacities, required renewable electricity generation, hydrogen distribution and refuelling infrastructures and end user applications. Finally, sections 4.3 and 4.4 estimate actual environmental and financial impacts as well as impacts on security of energy supply, employment and value added, respectively.

4.1 Estimated hydrogen demand by 2030 in the two scenarios

Today, conventional hydrogen is mainly used in industry and is produced from fossil fuels (e.g. through steam methane reforming of natural gas) or as a by-product from other chemical processes. Both the low and high scenarios assume that in 2030 renewable hydrogen will be domestically produced to partially substitute current conventional production and to cover additional demand (e.g. from the transport sector). The overall hydrogen demand for renewable or low-carbon hydrogen[81] by 2030 in the EU28 is estimated at ca. 40 TWh_{H2}/a in the low scenario and almost 180 TWh_{H2}/a in the high scenario (Figure 4-1).[82] The share of renewable or low-carbon hydrogen in final energy demand (11,120 TWh/a) amounts to 0.4% and 1.6% respectively, while its share in total final gas demand (2,342 TWh/a) amounts to 1.8% and 7.6% respectively, based on the final energy and gas demand values provided by the EUCO3232.5 scenario[83].

Figure 4-1 Renewable/low-carbon hydrogen demand in EU28 by 2030 in major sectors



Almost half of the assumed renewable or low-carbon hydrogen volumes is consumed in industry, mainly by refineries and steelmaking (Figure 4-2). In this context, refining is expected to be the most

[81] For hydrogen production see Chapter 4.2. Hydrogen demand is expected to be covered mainly by renewable hydrogen. Low-carbon hydrogen is an alternative option only in selected Member States.
[82] All figures related to hydrogen demand refer to the lower heating value.
[83] EUCO3232.5 scenario has been developed by the European Commission “to estimate the impact of the EU’s climate and energy targets for 2030.” It provides comprehensive scenario results on expected energy system layout by taking into account latest EU targets for GHG emission reduction, renewable energy targets (32%), and energy efficiency targets (32.5%) for all Member States. It is also officially used by the European Commission to evaluate the NECPs.
EC (2019). Technical Report on EUCO3232.5 Scenario. Available at https://ec.europa.eu/energy/en/data-analysis/energy-modelling/euco-scenarios

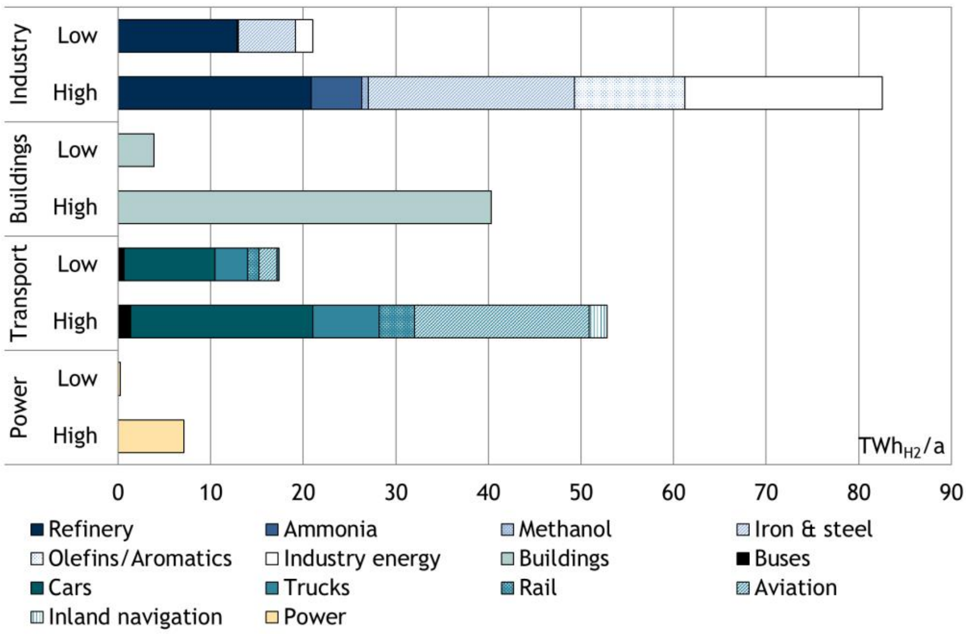
established market for renewable or low-carbon hydrogen by 2030 as it already consumes substantial amounts of conventional hydrogen which, from a technical perspective, can be easily substituted with other sources of hydrogen (13-21 TWh_{H2}/a). Moreover, additional costs for introducing renewable or low-carbon hydrogen into refining processes are limited.

In contrast, steelmaking based on direct reduction of iron ore by hydrogen requires investments in new production facilities and decommissioning of conventional blast furnaces. However, H_2-based steelmaking is one of the major technical options to decarbonise this sector and a number of European market players have already included it in their respective strategies or are launching pilot projects to test the technology (for the production of so called H_2-based direct reduced iron – H_2-DRI). Since the European steelmaking market is large, the new process would require substantial amounts of renewable or low-carbon hydrogen (6-22 TWh_{H2}/a).

The development of hydrogen use in the petrochemical industry (olefins and aromatics production) as well as for providing process heat (industry energy) is rather uncertain and varies substantially between the two scenarios. In the case of the petrochemical industry, the production of olefins and aromatics is characterised by a comparatively high specific hydrogen consumption indirectly via the methanol route. Hence, already small market shares of renewable or low-carbon H_2-based technologies in this sub sector (as assumed in the high scenario) might lead to large overall hydrogen demand (0-12 TWh_{H2}/a). In the case of process heat, the overall renewable or low-carbon demand will depend strongly on the underlying assumptions on its share to substitute natural gas in the gas sector (2-21 TWh_{H2}/a).

Although the ammonia industry is a large hydrogen consumer today, its product costs are sensitive to hydrogen prices and hence the renewable or low-carbon hydrogen demand is expected to remain limited even in the high scenario, due to global competition (0-5 TWh_{H2}/a). Methanol production is a comparatively small market in Europe and therefore the hydrogen demand from this sector will be limited (0-1 TWh_{H2}/a).

Figure 4-2 Renewable/low-carbon hydrogen demand in EU28 by 2030 in different sub-sectors



Similar to industry energy, the use of hydrogen in the buildings sector (mainly for heating purposes) depends on the expected blending rates of hydrogen into natural gas networks, and on the competitiveness of dedicated hydrogen networks. Therefore, due to a large uncertainty regarding the actual development of adequate distribution infrastructure, the demand varies to 4 and 40 TWh_{H2}/a respectively according to the underlying assumptions of both scenarios. This corresponds to 9 and 22% respectively of total renewable or low-carbon hydrogen demand in EU28.

The transport sector accounts for 17 and 53 TWh_{H2}/a respectively of the total renewable or low-carbon hydrogen demand in EU28 and is hence the second largest consumer sector. The major sub-sectors are passenger cars with 10 and 20 TWh_{H2}/a respectively and freight road transport with 3 and 7 TWh_{H2}/a respectively. In both sub-sectors, the availability of affordable vehicles and a sufficient refuelling station network are key prerequisites for the expected developments. Nevertheless, some applications such as large passenger cars and heavy-duty vehicles with a large driving range are typically hard to electrify and are well qualified for the use of hydrogen. The demand for synthetic fuels based on renewable or low-carbon hydrogen in the aviation sector strongly depends on the future strategy and concrete decarbonisation targets of the aviation industry. Given the uncertainty on the expected developments, the demand is estimated at 2 and 19 TWh_{H2}/a respectively indicating a potentially large consumption in the high scenario. The remaining sub-sectors, including buses (0.6-1.4 TWh_{H2}/a), trains (1-4 TWh_{H2}/a) and inland navigation (0.2-2 TWh_{H2}/a) have a lower potential in comparison to other sectors. However, in the case of buses and trains, there are already commercially available fuel cell-based applications on the market showing the importance of hydrogen technology in both sub-sectors.

In the power sector, the potential demand for renewable or low-carbon hydrogen accounts for only 0.2 and 7 TWh_{H2}/a respectively (1 and 4% respectively of total EU28 demand) mainly related to its use in CHP units of different sizes. The deployment of such CHP units depends on their competitiveness and development of corresponding infrastructure for pure H_2-CHPs. In some countries, additional demand might come from re-electrification of hydrogen in large power plants, which can be used as back-up for variable renewable power plants.

Figure 4-3 Renewable/low-carbon hydrogen demand per MS in the low scenario by 2030

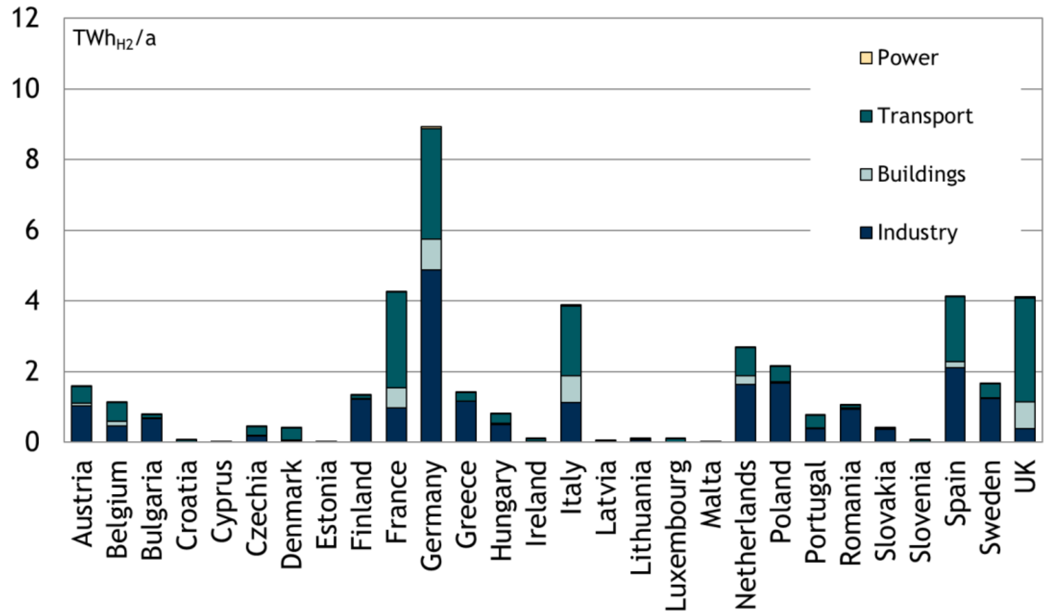


Figure 4-3 and Figure 4-4 present an overview of the renewable (or low-carbon) hydrogen demand per MS in both scenarios by 2030. The majority of the Member States have a demand for renewable or low-carbon hydrogen of less than 2.5 TWh_{H2}/a in the low scenario, and less than 7 TWh_{H2}/a in the high scenario representing a limited share of the total EU28 demand (29%-34%). In contrast, the “big six” Member States including Germany (9-42 TWh_{H2}/a), the UK (4-21 TWh_{H2}/a), France (4-20 TWh_{H2}/a), Italy (4-20 TWh_{H2}/a), Spain (4-17 TWh_{H2}/a), and the Netherlands (3-12 TWh_{H2}/a) are responsible for 66%-71% of the total demand in EU28. As depicted in Figure 4-5 for most Member States the share of green or low-carbon hydrogen in the final gas demand is below 15%. For small Member States (e.g. Cyprus and Malta) the assumed use of hydrogen can exceed their final natural gas demand. In all Member States, major renewable or low-carbon hydrogen demand is coming from either the industry or the transport sector. Among the “big six” Member States, Germany and the Netherlands have comparatively strong steel, chemical and petrochemical industries, such that for both countries major demand is coming from the industry sector (more than 50% of the respective country demand). In Italy and France, the demand in the low scenario is mainly based on the transport sector becoming more balanced in the high scenario. In Spain, similar shares of renewable and low-carbon hydrogen demand can be attributed to the industry and the transport sectors in both scenarios, whereas in the UK, most of the corresponding demand is driven by the transport sector in both scenarios. In some Member States with large feed-ins of variable renewable power such as Spain, Greece, Denmark and Ireland, hydrogen demand from the power sector becomes significant in the high scenario with a share of more than 15% in the respective country demand figures. More specific details at Member State level are presented in the country fiches.

Figure 4-4 Renewable/low-carbon hydrogen demand per MS in the high scenario by 2030

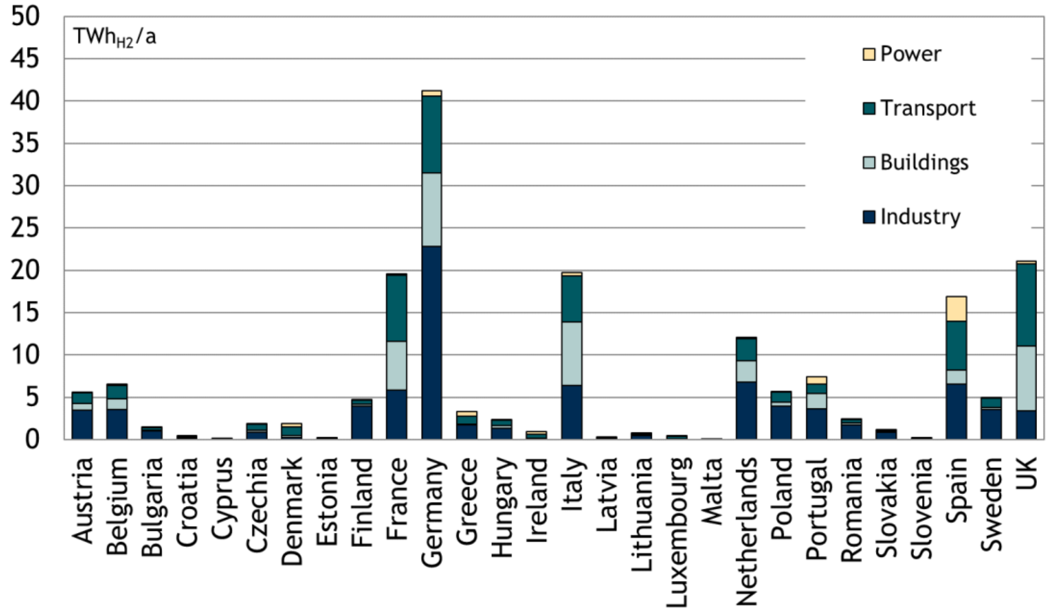
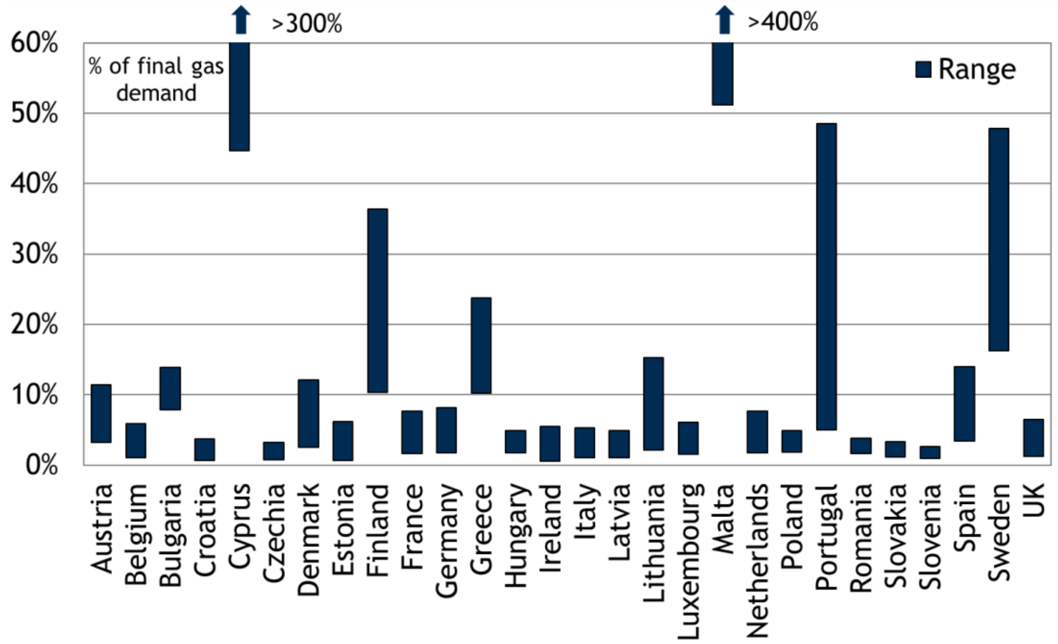


Figure 4-5 Renewable/low-carbon hydrogen demand per MS in the low and high scenario by 2030 as percentage of final gas demand



In the long term, the use of renewable or low-carbon hydrogen will help to decarbonise the end user sectors which are difficult to electrify due to lack of other suitable technical options. In particular this is true for the steelmaking industry and parts of the transport sector including heavy duty vehicles, large passenger cars, unelectrified railways and some of the buses. In addition, aviation and inland navigation will need specific solutions to reduce their GHG emissions. In this context, hydrogen-based synthetic fuels, so-called Power-to-Liquids (PtL), might be an option to decarbonise both sub-sectors. Moreover, in the chemical industry, conventional hydrogen can be easily replaced by renewable or low-carbon hydrogen with a significant effect on GHG emission reduction levels. Finally, storage of renewable or low-carbon hydrogen at large scale and its re-electrification in thermal power plants will be an important flexibility measure within the future energy system to balance variable power supply and energy demand.

Therefore, from the long-term perspective, it can be expected that the demand for renewable or low-carbon hydrogen will increase much more beyond the figures calculated for 2030 for the industry and transport sectors. Also, for the power sector, the demand might increase significantly depending on the actual design of the future energy systems and markets in Europe. In the building sector, however, further use of renewable or low-carbon hydrogen depends on the development of future overall energy demand in this sector as insulation of buildings and thus energy saving is the most effective way to reduce the GHG emissions. In addition, the deployment of other technical options such as heat pumps will influence the potential hydrogen consumption in this sector.

4.2 Hydrogen end users, infrastructure and generation

4.2.1 End user applications and refuelling station infrastructure

The expected deployment of the end user applications drives the demand for renewable and low-carbon hydrogen (see Table 4-1**Error! Reference source not found.**). In this context, a total of ca. 2.7-5.4 million fuel cell electric vehicles (FCEVs) are expected in 2030 on the European roads with passenger cars as the sub-sector with the highest number of units. As depicted in **Error! Reference source not found.**, more than 75% of the fuel cell road vehicles will be located in the large countries including Germany, Italy, France, the UK and Spain with at least 300,000 vehicles in the low scenario and 600,000 in the high scenario by 2030 in each country. The Dutch automotive market is in 2030 characterised by a high FCEV penetration rate leading to 100,000-200,000 road vehicles despite its smaller market size in comparison to the aforementioned countries. In contrast, Poland is traditionally a large automotive market but due to the low FCEV penetration rate, the Polish fleet size is similar to the Dutch market, indicating some untapped potential for renewable and low-carbon hydrogen in the Polish transport sector. Figure 4-7 illustrates the corresponding share of FCEVs in total number of vehicles on the road per Member State by 2030. Moreover, ca. 500-1,600 H_2-based trains are expected by 2030 to provide services on unelectrified railway lines. The demand for H_2-based synthetic fuels (PtL) from aviation and inland navigation accounts for ca. 1.5-14 TWh_{PtL}/a with more than 90% of the fuel attributed to aviation.

Table 4-1 Expected end user applications based on renewable or low-carbon hydrogen in the EU28 by 2030

Sector and sub-sector	Unit	Low scenario	High scenario	Market share (low)	Market share (high)
Passenger cars	N°	2,493,077	4,986,154	1.0%*	1.9%*
Buses	N°	7,973	16,944	0.9%*	1.8%*
Trucks	N°	187,341	382,638	0.5%*	1.1%*
Heavy duty vehicles	N°	21,861	44,509	0.6%*	1.2%*
Trains	N°	503	1,570	6.7%*	20.8%*
Aviation	GWh/a	1,327	12,606	0.2%**	1.9%**
Inland navigation	GWh/a	139	1,322	0.2%**	1.9%**
Micro CHP units	N°	177,610	803,356	0.4%**	1.8%**
Large CHP units	N°	224	2,509	0.02%**	0.2%**
Refining	% prod.	12.6%	20.5%		
Ammonia	% prod.	0.0%	5.0%		
Methanol	% prod.	0.0%	5.0%		
Iron & steel	% prod.	1.9%	6.8%		
Olefins & aromatics	% prod.	2,493,077	4,986,154		

** Based on current number of vehicles*
*** Based on expected heat demand from CHP and district heating according to 2030 values from the EUCO3232.5 scenario*

Figure 4-6 Number of fuel cell electric road vehicles per MS by 2030

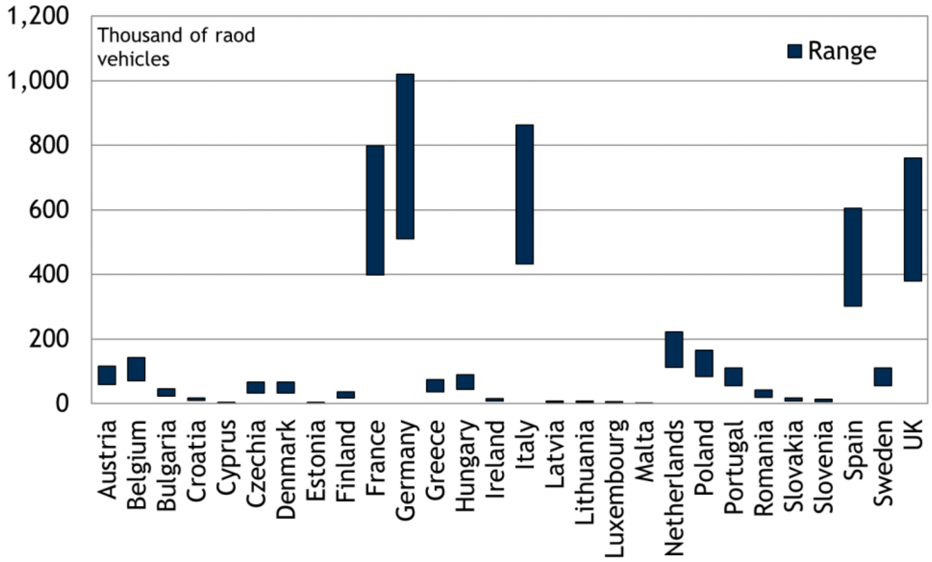
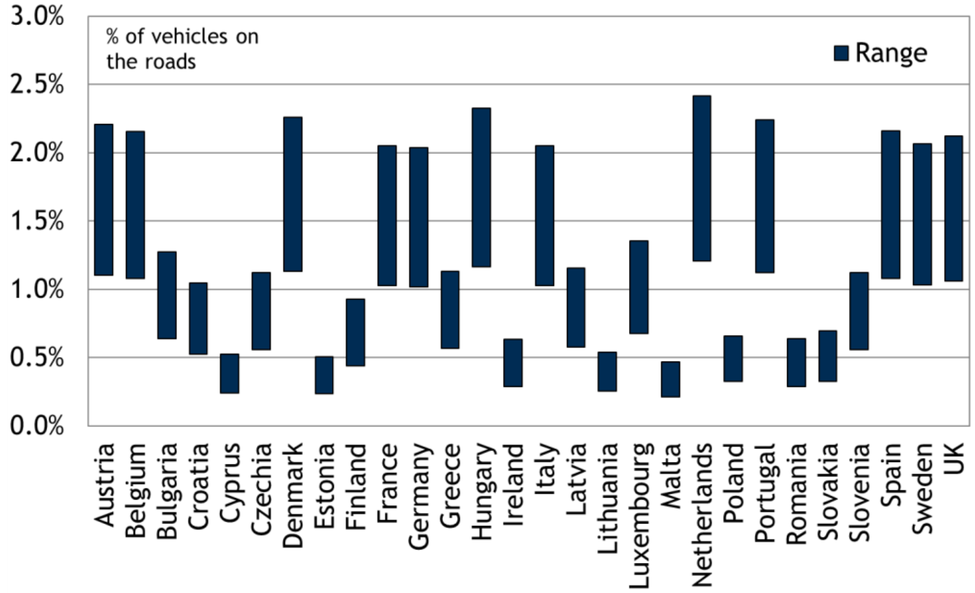


Figure 4-7 Number of fuel cell electric road vehicles per MS by 2030 as share of total vehicles on the road



In the buildings sector, ca. 180,000-800,000 combined heat and power (CHP) units are expected across Europe by 2030. Most of them would be installed in large countries with substantial demand for heating, such as Germany, France, the UK and Italy, with a combined capacity of 130,000-590,000 units.

In the industry sector, refining is the most advanced sub-sector with respect to the use of renewable or low-carbon hydrogen. Based on the assumptions of this study, 13%-21% of the European refining production could switch from conventional to renewable or low-carbon hydrogen, mainly in countries with traditionally large refining capacities and strong development of renewable and low-carbon hydrogen supply technologies such as Germany or the Netherlands. The steelmaking industry might base ca. 2%-7% of its production on H_2-consuming processes. In particular, in the high scenario one could expect that the companies which have already included hydrogen-based steel production in their respective strategies or are launching demo projects might convert one blast furnace into H_2-based production facilities of the same capacity. In the high scenario ca. 7 blast furnaces are assumed to be replaced by H_2-DRI plants in Germany (3 H_2-DRI plants), Austria (1), Sweden (1) and Finland (2) by 2030. In the ammonia and methanol industries, up to 5% of the overall production might be based on renewable or low-carbon hydrogen whereas for the petrochemical industry (olefins and aromatics) 1.5% may be achieved in the high scenario.

As presented in Figure 4-8 and Figure 4-9 ca. 4,500-8,100 hydrogen refuelling stations (HRS) are required to serve the aforementioned fuel cell vehicles in the EU28 by 2030. Their distribution between the Member States follows the development of the FCEVs in the different countries. Hence, most of the refuelling stations should be placed in Germany (800-1,400 HRS), Italy (700-1,200 HRS), France (600-1,100 HRS), the UK (600-1,100 HRS) and Spain (500-900 HRS). In the Netherlands and Poland, the number of required HRS is substantially smaller with 200-400 in the Netherlands and 150-300 in Poland. Figure 4-10 depicts the hydrogen refuelling stations as a historical share of conventional refuelling stations within a range of 1%-13%.

Figure 4-8 Number of hydrogen refuelling stations in the EU28 by 2030

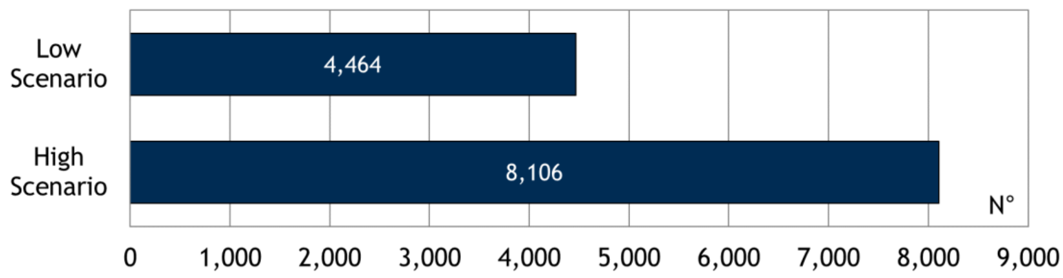


Figure 4-9 Number of hydrogen refuelling stations per MS by 2030

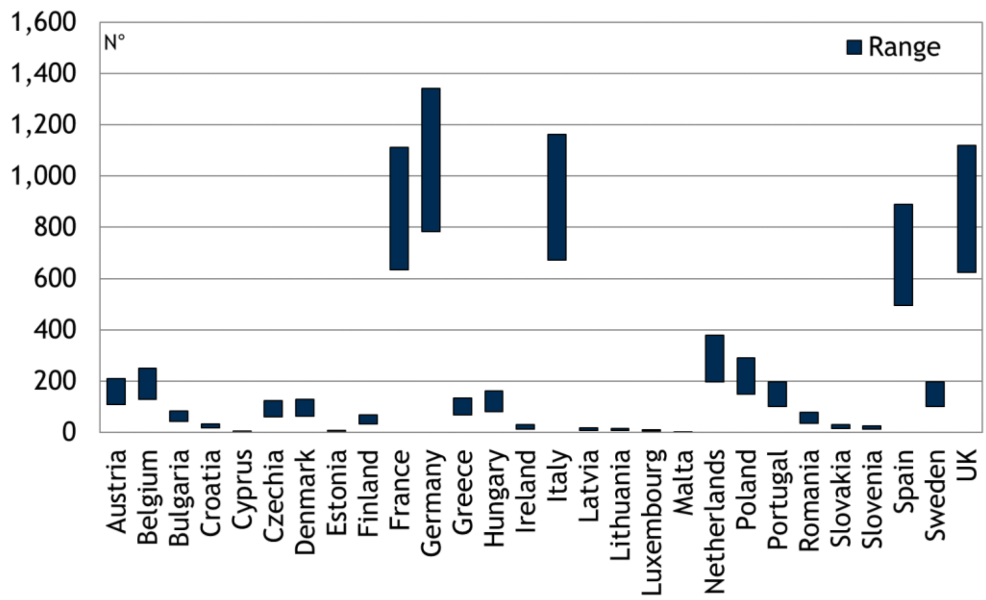
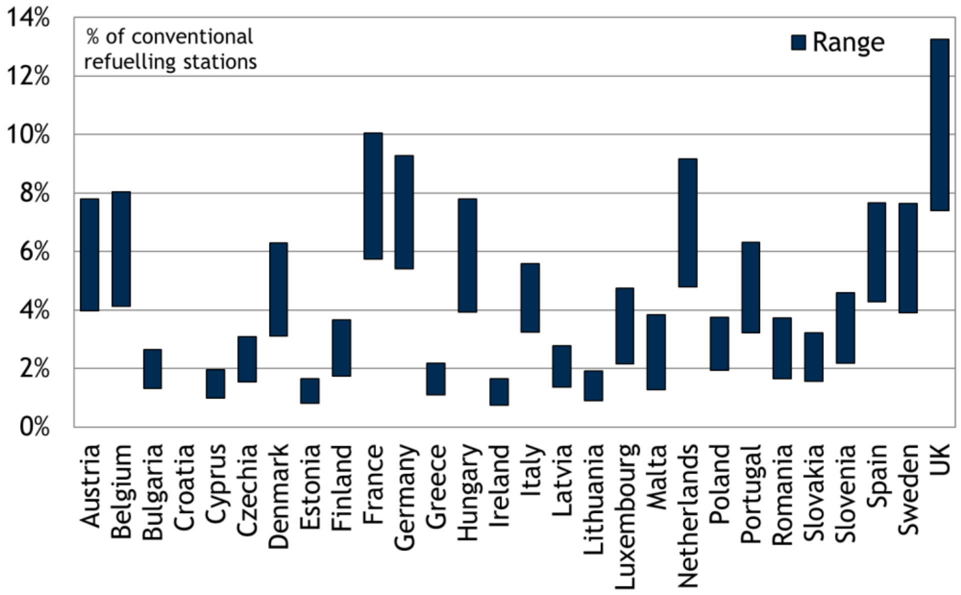


Figure 4-10 Hydrogen refuelling stations per MS by 2030 as a historical share of conventional refuelling stations



4.2.2 *Renewable or low-carbon hydrogen generation*

In order to estimate the expected capacities for hydrogen generation, this study assumes that the entire demand for renewable or low-carbon hydrogen will be met by domestic supply at national level (i.e. there is no hydrogen trade between Member States and no import from non-EU countries). For renewable hydrogen produced via electrolysis from variable renewable power, the required electrolysis capacity in EU28 by 2030 is 13 and 56 GW_{el} respectively with an average utilisation of 4,800 full load hours (Figure 4-11). Following the demand, ca. 8-39 GW_{el} (64%-70% of the overall capacity) are installed in six Member States including Germany, Italy, the UK, France, the Netherlands and Spain (Figure 4-12).

Figure 4-11 Electrolysis capacity in EU28 by 2030

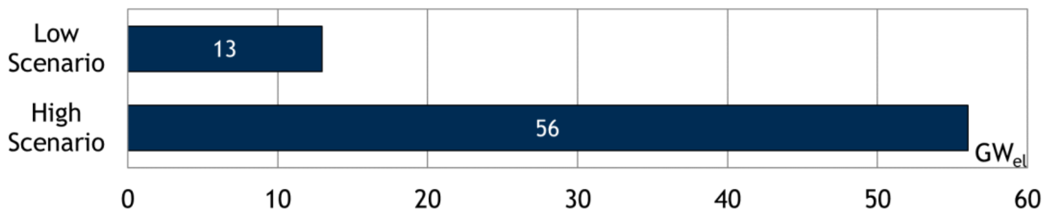
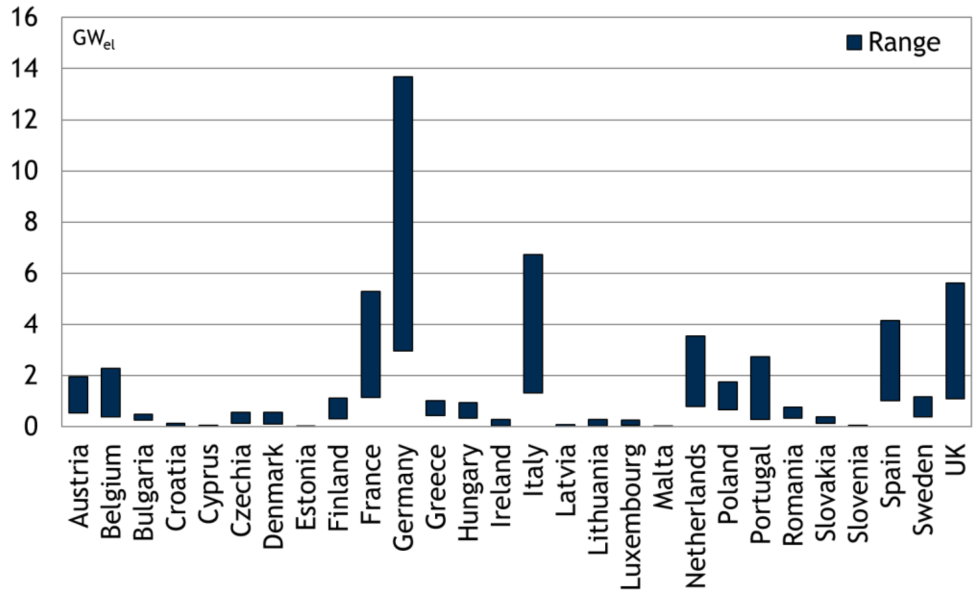
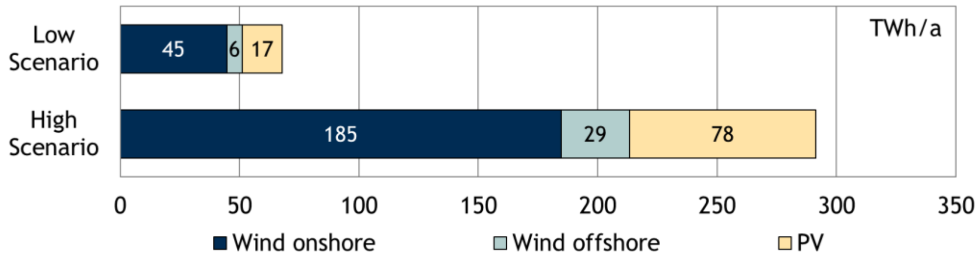


Figure 4-12 Electrolysis capacity per MS by 2030



The corresponding consumption of renewable power amounts to 68 and 291 TWh/a respectively (Figure 4-13). According to renewable energy potentials in the EU28, wind onshore is the major energy source (66% of the overall energy demand) followed by solar power (25% of the overall energy demand). This means that domestic production of renewable hydrogen generation would require new capacities in wind power plants (onshore and offshore) of 20-84 GW and additionally in solar power plants of 17-78 GW across Europe by 2030. However, this additional demand for renewable electricity accounts for only 0.6%-2.6% of the overall renewable power potential in Europe.

Figure 4-13 Renewable electricity input for hydrogen production in EU28 by 2030



Primary energy input for renewable hydrogen per Member State by 2030 is presented in Figure 4-14 and Figure 4-15 for the low and the high scenario, respectively. As with the expected hydrogen demand and electrolysis capacity, most of the renewable electricity is used in the “big six” Member States responsible for 45-208 TWh/a of power consumption. In most Member States, wind onshore is the major energy source, as it is for the entire EU28. However, there are a few exceptions: in Malta, Luxembourg and Portugal, energy supply is mainly based on solar power whereas in a few other Member States including Germany, Belgium and Slovenia, the technology split is balanced. In the Netherlands wind offshore plays a dominant role.

Figure 4-14 Renewable electricity input for hydrogen production per MS in the low scenario by 2030

Figure 4-15 Renewable electricity input for hydrogen production per MS in the high scenario by 2030

Alternatively, low-carbon hydrogen can be produced via steam methane reforming (SMR) in combination with carbon capture and storage (CCS). In Member States with a high readiness for CO_2 storage (i.e. Germany, the Netherlands, and the UK), this might be an additional option for hydrogen generation. Assuming that the overall country-specific hydrogen demand as estimated in Chapter 4.1 would be provided by SMR with CCS, the required SMR capacities in the aforementioned Member States would be 2-9 GW_{H2} based on a utilisation rate of 95% or 8,322 full load hours (Table 4-22). The corresponding natural gas consumption is 23-108 TWh/a (2%-11% of the final natural gas demand in the respective countries) to satisfy the demand for low-carbon hydrogen of 16- 74 TWh_{H2}/a (Table 4-32).

Table 4-2 SMR with CCS capacity in EU28 by 2030

Installed SMR capacity (GW)	Low scenario	High scenario
Germany	1.1	5.0
Netherlands	0.3	1.5

UK	0.5	2.5
Total	**1.9**	**8.9**

Table 4-3 Natural gas consumption by SMR with CCS in EU28 by 2030

Member State	NG demand (TWh/a) Low scenario	NG demand (TWh/a) High scenario	Share of final NG demand - Low Scenario	Share of final NG demand - High Scenario
Germany	13.0	59.7	2.6%	11.8%
Netherlands	3.9	17.5	2.5%	11.1%
UK	6.0	30.6	1.8%	9.3%
Total	**22.8**	**107.8**	**2.3%**	**10.9%**

4.3 Environmental and financial impacts

4.3.1 Environmental impact

According to the results of the EUCO3232.5 scenario[84] the GHG emissions in the EU28 are expected to decrease from ca. 4.6 Gt_{CO2}/a in 2015 to 3.1 Gt_{CO2}/a in 2030 in order to achieve the European decarbonisation targets (Figure 4-16). The remaining GHG reduction gap towards the 2030 target of ca. 1.5 Gt_{CO2}/a can be partially closed by the substitution of fossil fuels by renewable or low-carbon hydrogen. Based on the assumptions of this study, renewable hydrogen can contribute to a GHG emission reduction of 20 and 67 Mt_{CO2}/a respectively, corresponding to 1.4 and 4.6% respectively of the reduction gap at EU28 level.

On the Member State level, the largest contribution is provided by six Member States (Germany, the UK, France, Italy, the Netherlands and Spain) as well as countries with substantial use of renewable hydrogen in steelmaking (Austria, Sweden and Finland) (see Figure 4-17). Together, these nine countries could decrease GHG emissions in the EU28 by 17-56 Mt_{CO2}/a, more than 85% of the GHG emission reduction related to renewable hydrogen in the EU28.

[84] EUCO3232.5 scenario has been developed by the European Commission "to estimate the impact of the EU's climate and energy targets for 2030." It provides comprehensive scenario results on expected energy system layout by taking into account latest EU targets for GHG emission reduction, renewable energy targets (32%), and energy efficiency targets (32.5%) for all Member States. It is also officially used by the European Commission to evaluate the NECPs. European Commission (2019a). Technical Report on EUCO3232.5 Scenario.

Figure 4-16 Expected renewable H_2-related GHG emission reduction in the EU28 by 2030

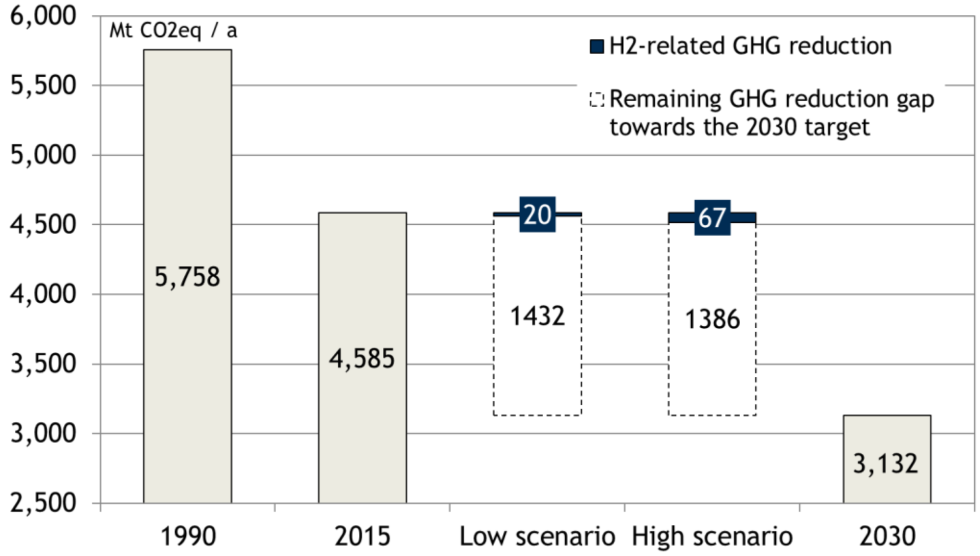
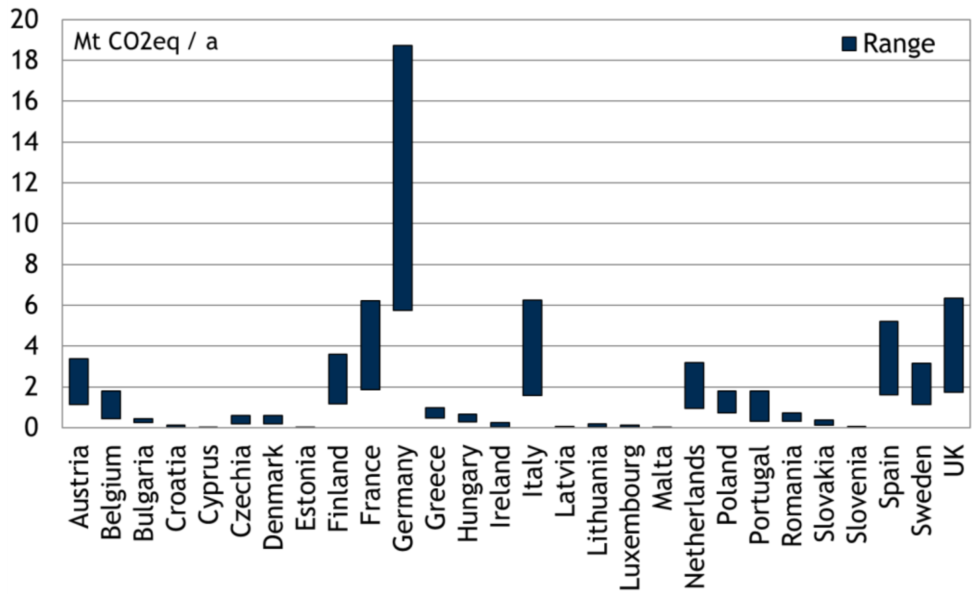
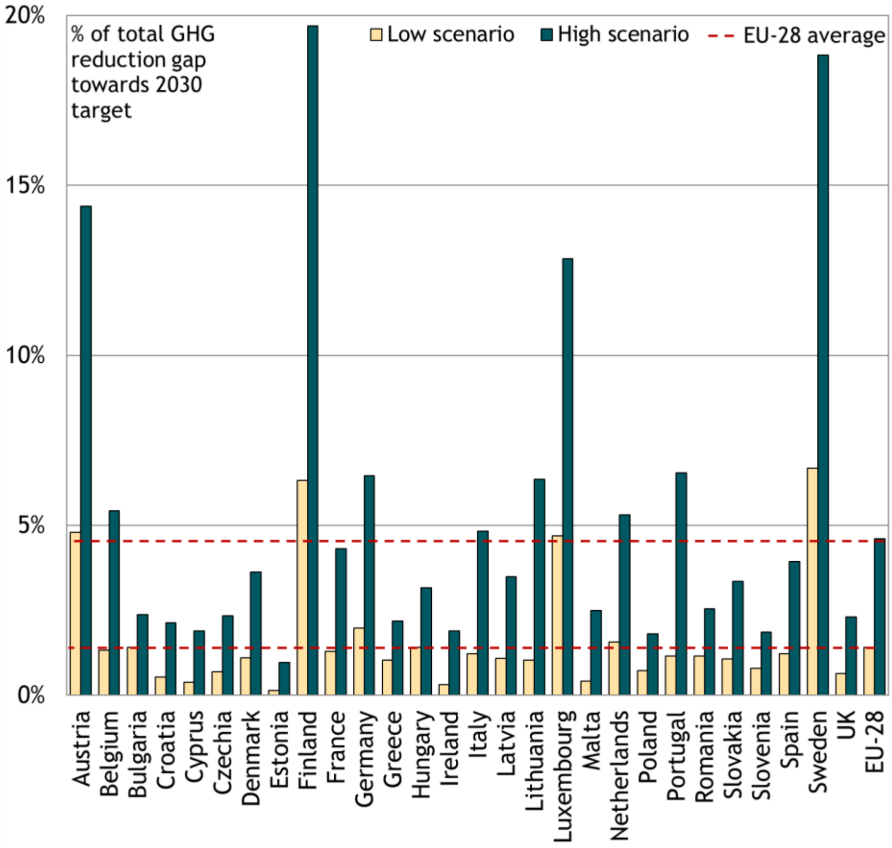


Figure 4-17 Expected renewable H_2-related GHG emission reduction per MS by 2030



The expected renewable H_2-related GHG emission reduction as a share of total reduction towards the 2030 target per Member State by 2030 is shown in Figure 4-18. Four Member States including Austria, Finland, Luxembourg and Sweden might benefit strongly from the use of renewable or low-carbon hydrogen with a share in the respective GHG emission reduction gap of 5%-7% in the low scenario and 12% to 20% in the high scenario. Eight other Member States including Belgium, Bulgaria, Germany, Hungary, Italy, Lithuania, the Netherlands and Portugal could also achieve above average rates in the low and/or high scenario.

Figure 4-18 Expected renewable H_2-related GHG emission reduction as a share of total reduction towards 2030 target per MS by 2030 (dashed lines represent EU28 average in high and low scenarios)



In case of low-carbon hydrogen production as a potential alternative to renewable hydrogen production in Germany, the Netherlands and the UK, the environmental impact of this option in these countries is very similar. Based on a CO_2 capture rate of 90%, the overall GHG emission savings in EU28 are 0.8-2.8 Mt CO_2/a lower (i.e. 19.6 and 64 Mt CO_2/a respectively, corresponding to 1.3% and 4.3% respectively of the reduction gap at EU28 level).

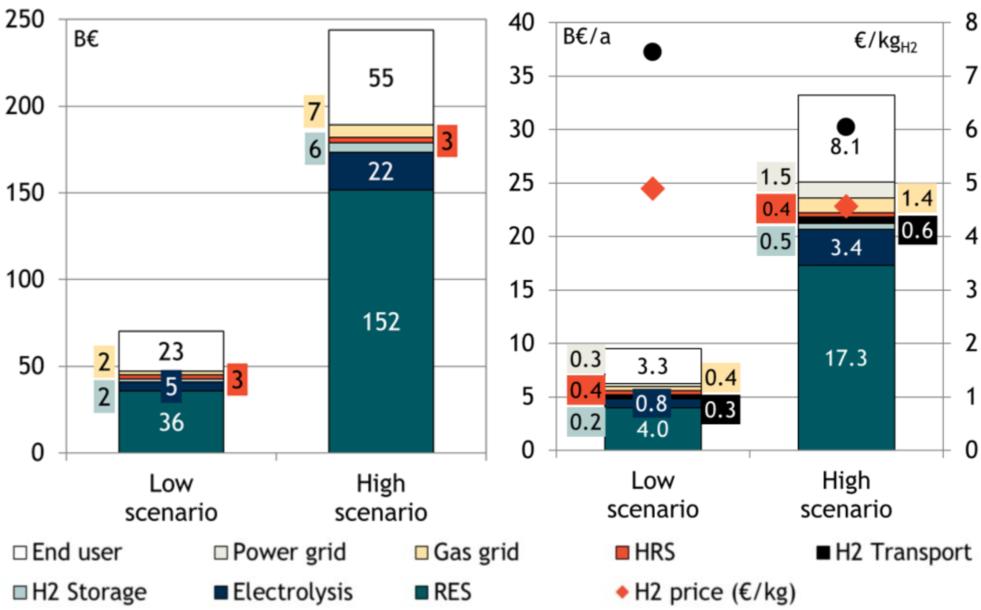
4.3.2 Financial impact

The financial impact of renewable or low-carbon hydrogen deployment includes the calculation of the corresponding investments until 2030, the annual costs as well as the expected hydrogen cost by 2030 at EU28 and Member State level. Based on the techno-economic assumptions of this study, the overall accumulated investment in renewable hydrogen technologies in the EU28 amounts to 71 and 249 billion EUR respectively (Figure 4-19 left). The annual costs including annualised investments, fixed operation and maintenance costs, and all other variable costs amount to 10 billion EUR/a and 33 billion EUR/a respectively in 2030 (Figure 4-19 right). Renewable energy supply (RES) is the major cost driver with 50%-60% of total investments and 40%-50% of annual costs. The average price for electricity consumed by electrolysis is 65 €/MWh at EU28 level[85]. In addition, end user applications account for 20%-30% of the overall investments and annual costs followed by electrolysis units with almost 10%. The investments and annual costs related to infrastructure including power and gas grids, refuelling stations and renewable hydrogen storage are much lower (altogether 7%-10% of total investments, or 13%-15% of

[85] This is a conservative estimate based on Asset (2018); lower costs are possible based on stronger cost reductions between today and 2030.

total annual costs in 2030). The ranges for the corresponding figures at Member State level are presented in Figure 4-21 and Figure 4-22. Again, major investments and annual costs occur in the same six Member States (Germany, the UK, France, Italy, the Netherlands and Spain).

Figure 4-19 Accumulated investment needs (left) and annual costs (right) related to renewable hydrogen technologies in EU28 by 2030



The presented annual costs can be considered as gross values. This means that part of the aforementioned costs would occur also in a reference case without any renewable hydrogen use, as there is a general demand for feedstock (e.g. for steelmaking), energy (e.g. for heating in buildings) and mobility (e.g. for passenger cars and heavy-duty vehicles) irrespective of the underlying technology. Hence, the net costs of renewable hydrogen are lower. Taking into account the annual costs of avoided fossil fuel imports of 3-9 billion EUR/a, the net costs for renewable hydrogen result in 6-24 billion EUR/a (Figure 4-20).

Figure 4-20 Net (of avoided imported fossil fuel) annual costs related to renewable hydrogen technologies in EU28 in 2030

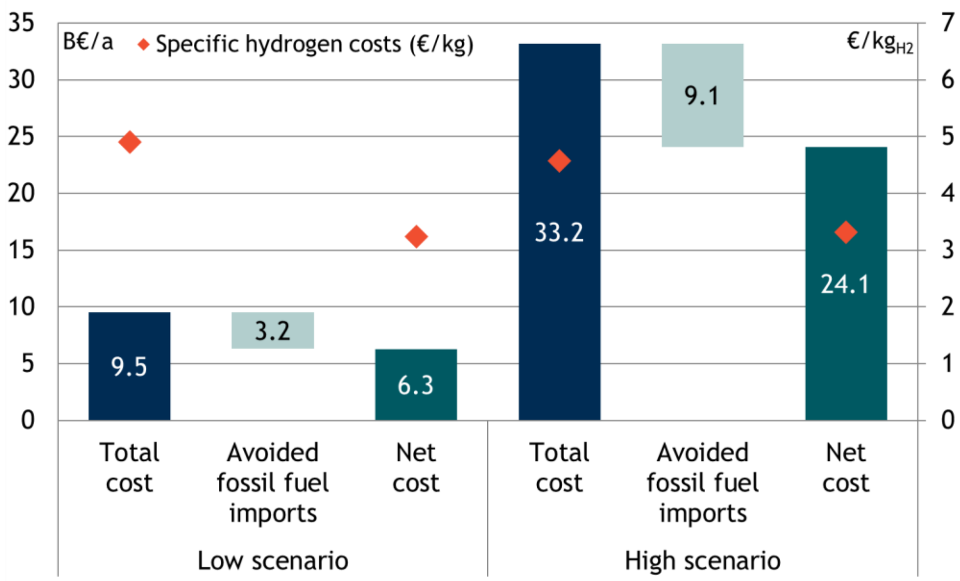


Figure 4-21 Investment needs in renewable hydrogen technologies per MS by 2030

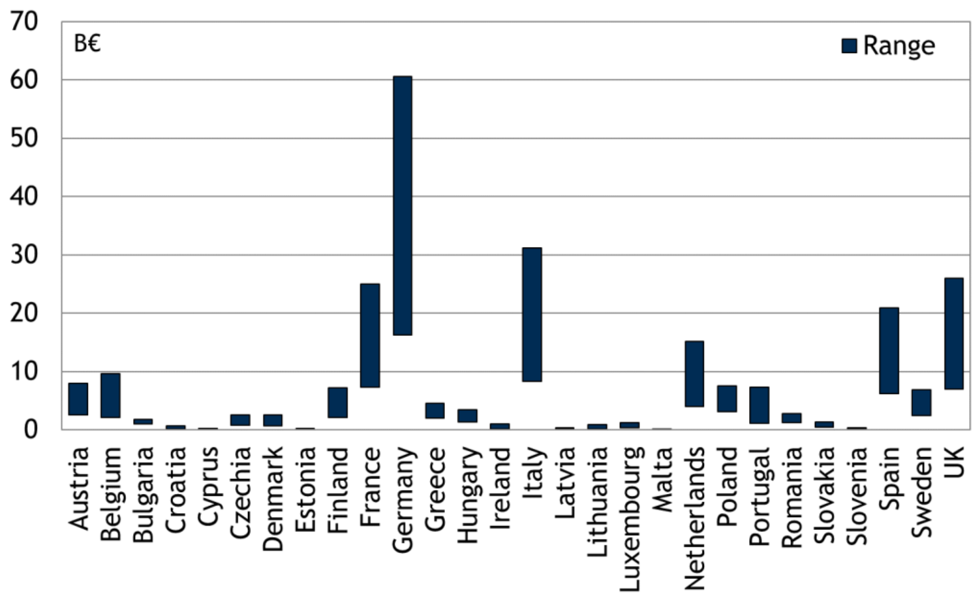
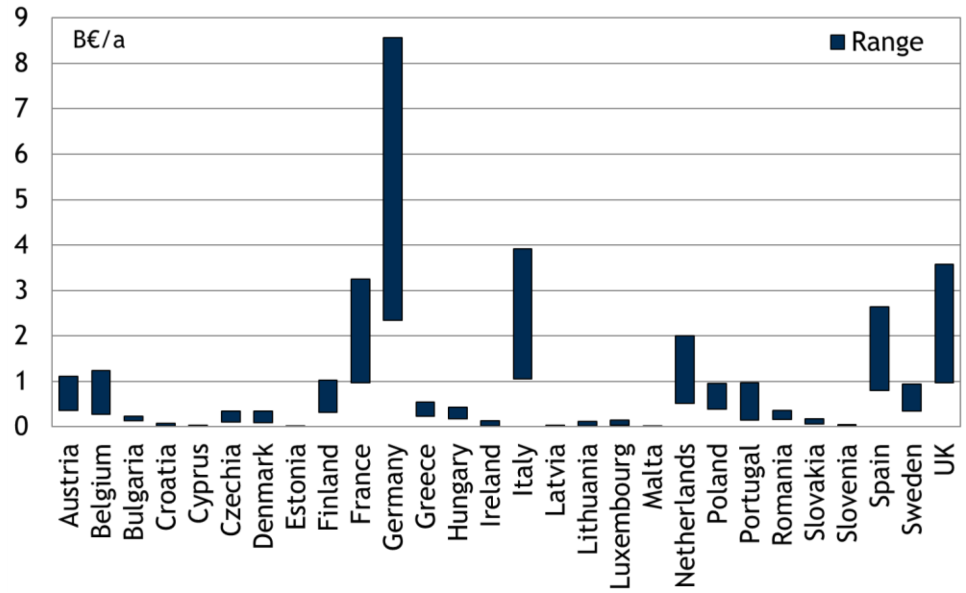
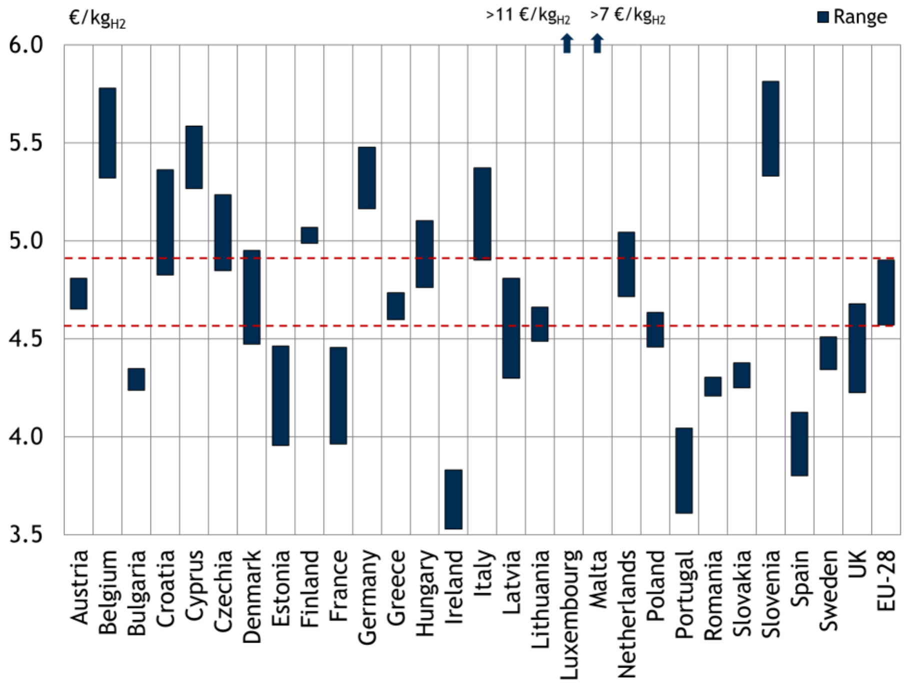


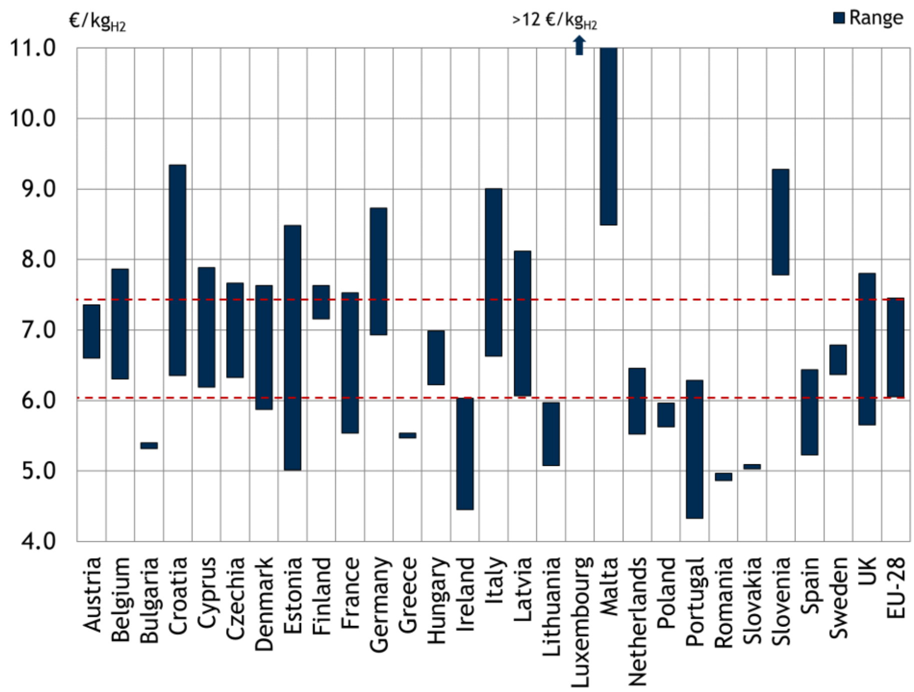
Figure 4-22 Annual costs related to renewable hydrogen technologies per MS by 2030



The average renewable hydrogen delivery costs at EU28 level for all sectors range from 4.6 to 4.9 EUR/kg$_{H2}$. These costs are calculated as total annual costs excluding end user costs divided by the overall consumption of renewable hydrogen. Hence, they correspond to renewable hydrogen costs without any margins or taxes that are paid by end-users, such as FCEV refuelling station charges, or industrial consumer charges upon delivery at sites. The differences between the low and high scenarios are due to a better utilisation of hydrogen refuelling stations in the high scenario. As presented in Figure 4-23 (top), the ranges for average renewable hydrogen delivery costs can vary significantly between Member States. The major factors responsible for the differences are the costs related to renewable energy supply and in some countries, hydrogen storage. In 12 Member States (Bulgaria, Estonia, France, Ireland, Lithuania, Poland, Portugal, Romania, Slovakia, Spain, Sweden and the UK) the average renewable hydrogen delivery costs are below the EU28 average as these countries have a comparatively cheap renewable power supply (RES) and the share of storage costs in total costs is rather small based on favourable RES feed-in profiles. In 10 Member States (Belgium, Croatia, Cyprus, Czechia, Finland, Germany, Italy, Luxembourg, Malta and Slovenia), the renewable hydrogen cost is above the EU28 average as in these countries, RES production is comparatively expensive and/or the need and cost for additional renewable hydrogen storage due to unfavourable RES feed-in profiles is high. In the remaining six Member States the renewable hydrogen cost is similar to the EU28 average. The specific hydrogen costs including the end-user related-costs such as FCEVs or CHPs are calculated as overall annual costs divided by the overall consumption of renewable hydrogen and are shown in Figure 4-23 (bottom). They are typically 10%-90% higher than the above-mentioned renewable hydrogen delivery costs and for most Member States within a similar range as the EU28 average.

Figure 4-23 Expected renewable hydrogen delivery costs excluding end-user related costs (top) and overall specific hydrogen costs including end-user related costs (bottom) per MS by 2030





In case of low-carbon hydrogen production in Germany, the Netherlands and the UK, the overall investments (13-33 billion EUR) and annual costs (2.6-8.4 billion EUR/a) are lower than for renewable hydrogen (Figure 4-24 and Figure 4-25). This difference is mainly due to the comparatively low assumed natural gas prices of 25 EUR/MWh and low assumed CCS costs of ca. 18 EUR/t_{CO2}. Accordingly, the average low-carbon delivery cost (excluding end user equipment) ranges well below 3 €/kg_{H2} (Figure 4 25). The difference in the hydrogen cost between the two scenarios is due to the different utilisation rates of the hydrogen refuelling infrastructure.

Figure 4-24 Investment needs related to SMR with CCS supply and use per MS by 2030

Investment needs (billion EUR)	Low scenario	High scenario
Germany	7.1	19.1
Netherlands	1.4	3.9
UK	4.0	10.3
Total	**12.5**	**33.2**

Figure 4-25 Expected annual costs and H2 cost related to SMR with CCS supply and use per MS by 2030

Country	Annual costs (billion EUR/a) Low scenario	Annual costs (billion EUR/a) High scenario	H_2 price (EUR/kg_{H2}) Low scenario	H_2 price (EUR/kg_{H2}) High scenario
Germany	1.5	4.8	2.4	2.1
Netherlands	0.3	1.1	2.4	2.2
UK	0.8	2.5	3.0	2.5
Total	**2.6**	**8.4**	**2.6**	**2.2**

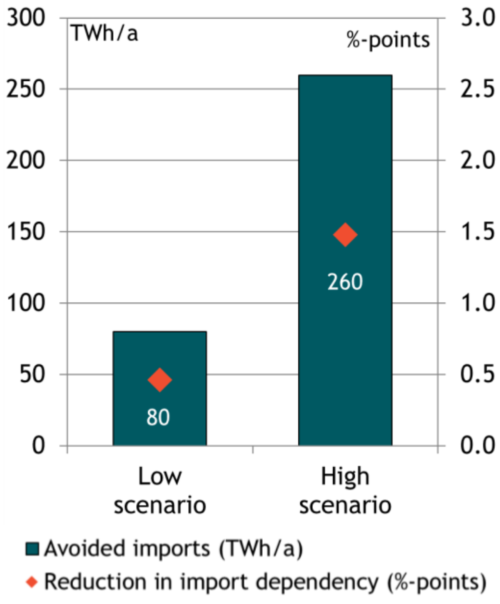
4.4 Impacts of renewable hydrogen deployment on security of energy supply, employment and value added

4.4.1 *Impact on security of energy supply*

The use of renewable hydrogen as presented in previous chapters will help MSs avoid imports of fossil fuels and thus decrease their import dependency and increase their security of energy supply. For the EU28, avoided fossil fuel imports by 2030 account for 80 and 260 TWh/a respectively, improving the level of security of supply (i.e. decreasing the degree of import dependence) by 0.5-1.5 %-points from 51% in 2030 as anticipated by the EUCO3232.5 Scenario[86] (see Figure 4-26). Oil (40-95 TWh/a) and natural gas (25-95 TWh/a) are the major energy carriers which can be replaced by domestic renewable or low-carbon hydrogen. In Member States with significant steel production, avoided coal imports are also important.

[86] European Commission (2019a). Technical Report on EUCO3232.5 Scenario.

Figure 4-26 Avoided fossil fuel imports and changes in the level of security of supply in EU28 by 2030



In absolute figures (see Figure 4-27), Germany will avoid the largest amount of fossil fuels with 20-67 TWh/a by 2030 (ca. 20%-25% of total avoided imports in EU28) with an important role of avoided coal imports related to steelmaking (ca. 50% of total German avoided imports). Other major countries which will avoid fossil fuel imports include France (8-27 TWh/a), the UK (7-27 TWh/a), Spain (7-27 TWh/a) and Italy (7-26 TWh/a), with main impacts on the oil imports in the low scenario and similar impacts on oil and natural gas imports in the high scenario.

In relative figures (see Figure 4-28), the level of security of energy supply increases in a wide range of 0.1-1 %-points in the low scenario and 0.2-3.5 %-points in the high scenario. Austria, Finland, Germany and Sweden are Member States which profit from the use of renewable and low-carbon hydrogen in steelmaking and have an above average increase in the level of security of energy supply. Also, Portugal benefits from substitution of natural gas imports. In addition, the three Southern European countries Italy, Greece and Spain can reduce their respective energy import dependencies in a more pronounced way than most of the EU28 Member States, due to their comparatively high historical levels of import dependency and the role of oil imports for the transport sector.

Figure 4-27 Avoided fossil fuel imports per MS by 2030

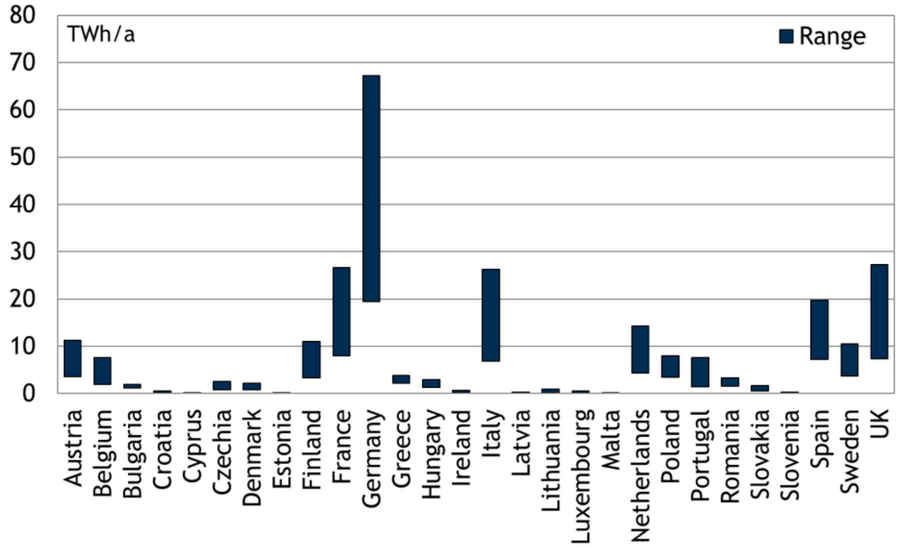
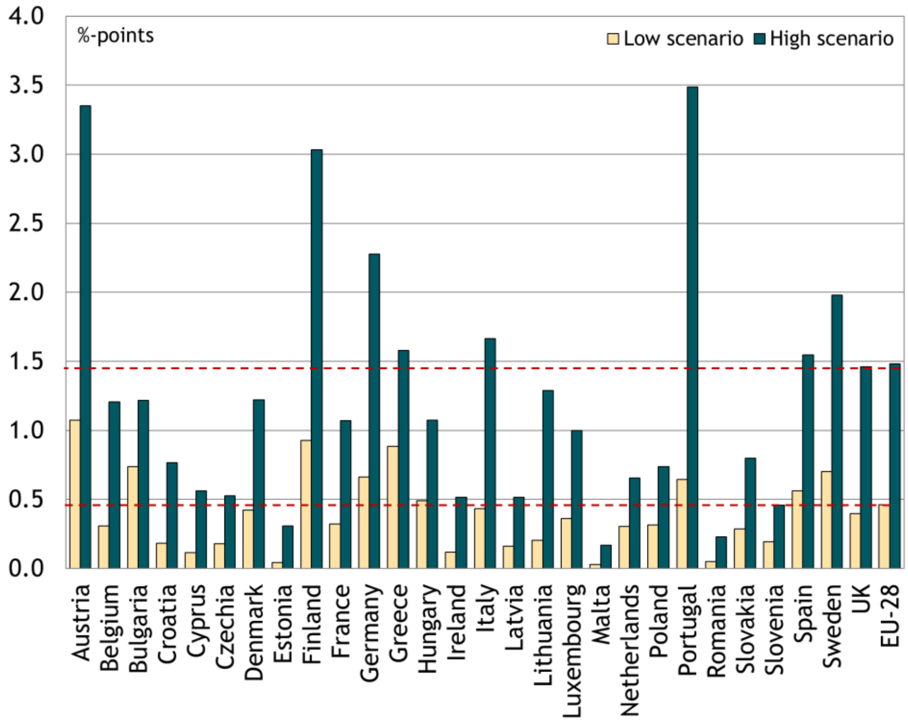


Figure 4-28 Improvements of the level of security of energy supply per MS by 2030



4.4.2 *Impact on employment and value added*

The analysis of value added shows that, depending on the scenario, 7.6 billion or 29 billion EUR of value added can be generated annually in the whole EU28, by investment in and operation of hydrogen technologies (taking into account both direct and indirect effects). As illustrated in Figure 4-29, the value added represents respectively 80% or 90% of the annual costs. The major share of the value added would be created in the five largest countries (Germany, Italy, United Kingdom, France and Spain). Other countries with high value added (taking into account the relatively smaller size of their economy) are the Netherlands, Belgium, Austria, Finland and Greece. The distribution of value added per Member State is represented in Figure 4-30 and Figure 4-31.

As shown in Figure 4-32, most of the value added is expected to be created by building and operating the renewable electricity plants that provide energy to electrolysers. A significant share of value added would also be created by the development of hydrogen transport infrastructure (pipelines, storage and also transport by trucks). In the end-user segment, most value added is expected to be created in the industrial applications and fuel-vehicles production and operation.

Figure 4-29 Value Added as share of Annual Costs - EU28

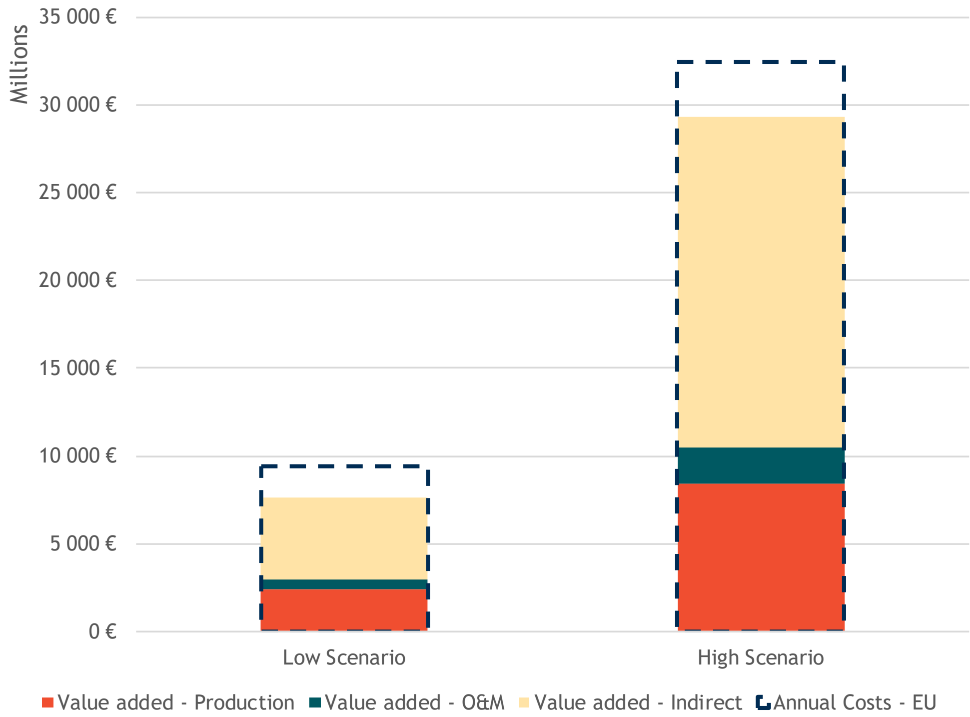


Figure 4-30 Value Added per Country - Low Scenario

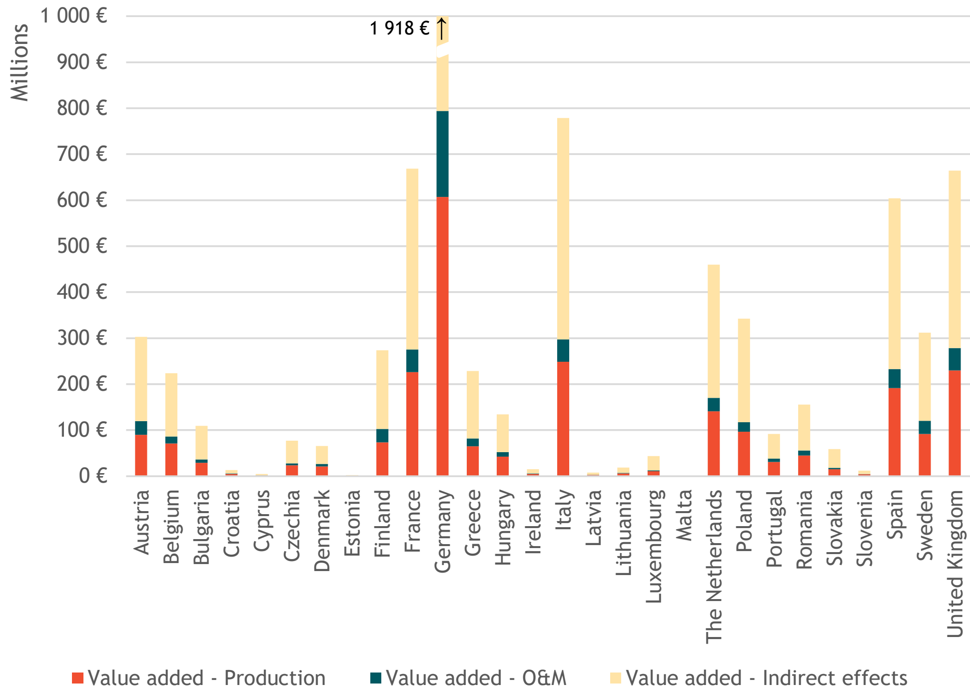


Figure 4-31 Value Added per Country - High Scenario

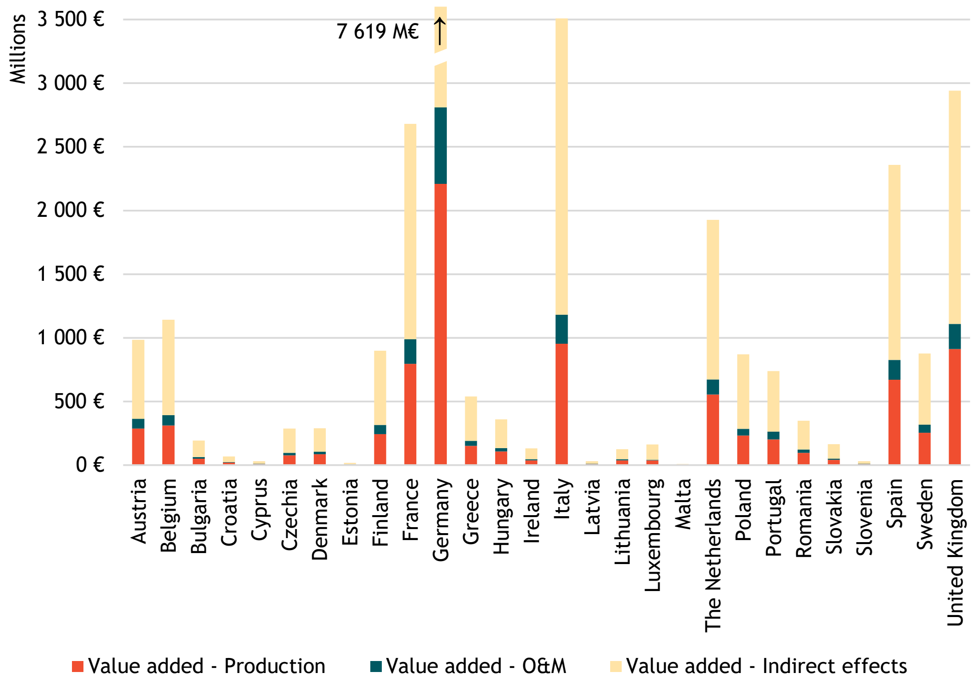
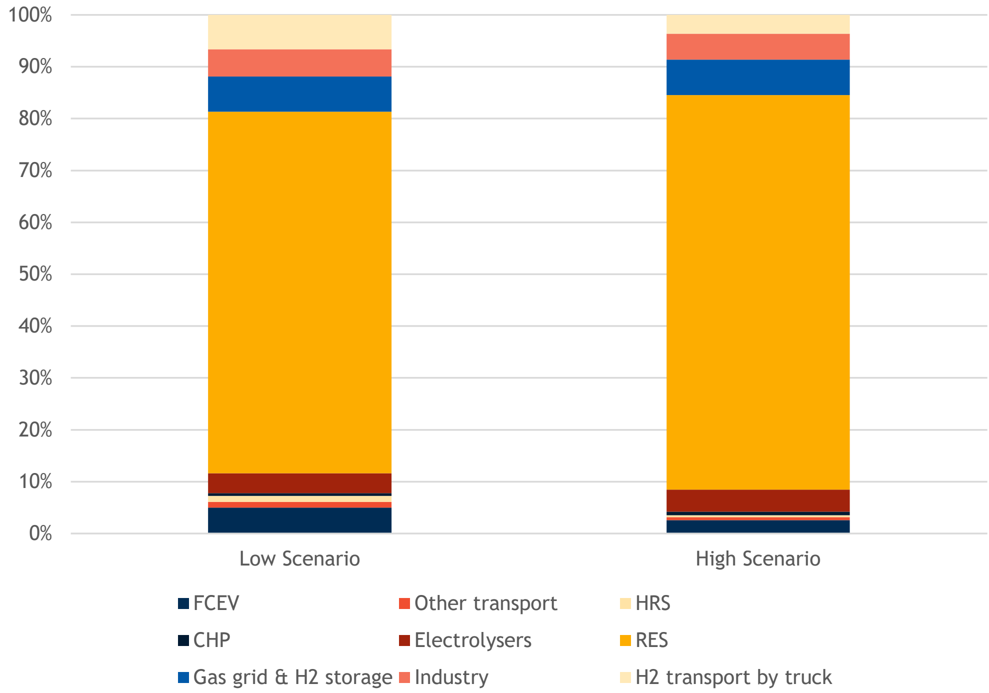


Figure 4-32 Value Added Share per Value Chain Segment - EU28



Hydrogen-related investments and operations are estimated to generate in 2020-2030 employment of 29 270 – 106 980 direct jobs (in production and operations & maintenance) and contribute to further 74 790 – 250 650 indirect jobs, depending on the scenario (these numbers are calculated as annual full-time equivalent jobs). In sum, the hydrogen economy could by 2030 generate 104 060 – 357 630 jobs. The distribution of employment effects in the High and Low Scenario per Member States is shown in Figure 4-33 and Figure 4-34. The most significant portion of employment will be created by building and operating renewable electricity sources, followed by activities in the automotive industry (in particular the production of fuel cell cars). The distribution of employment effects per value chain segment is shown in Figure 4-35.

Figure 4-33 Impact on Employment per Country - Low Scenario

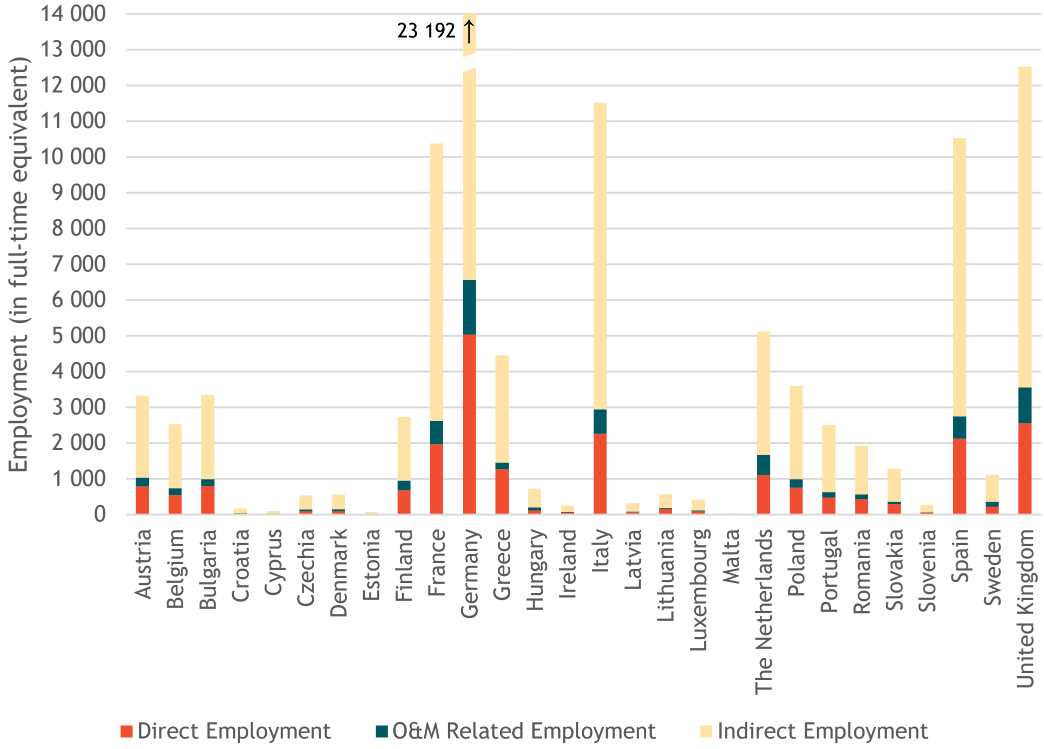


Figure 4-34 Impact on Employment per Country - High Scenario

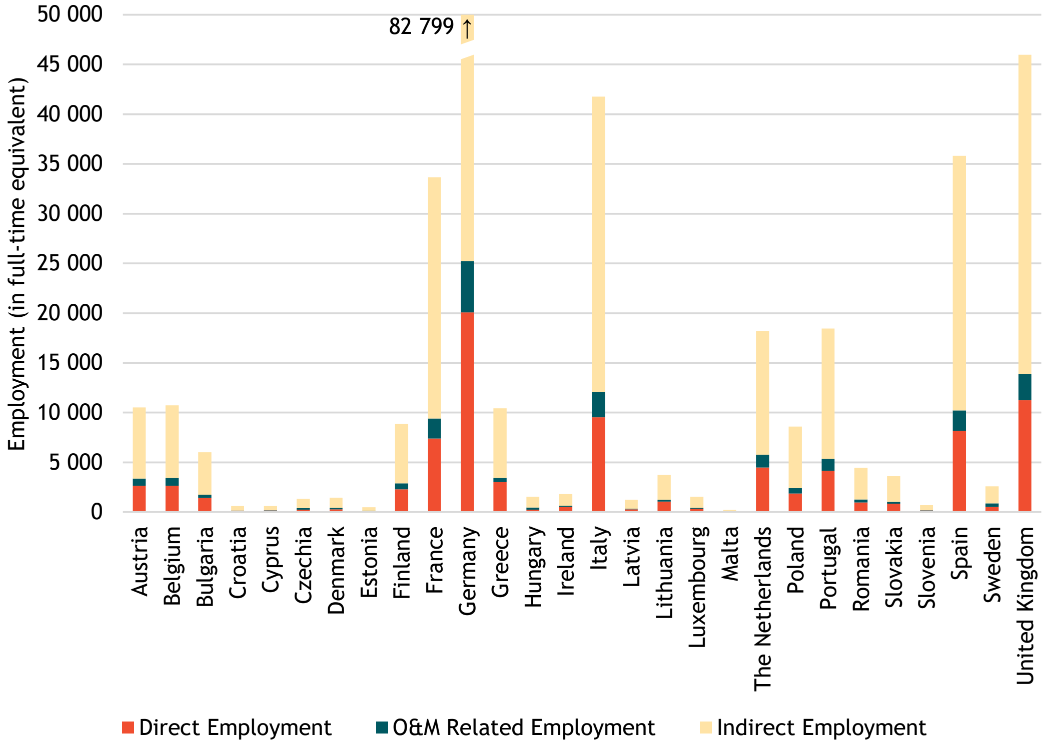
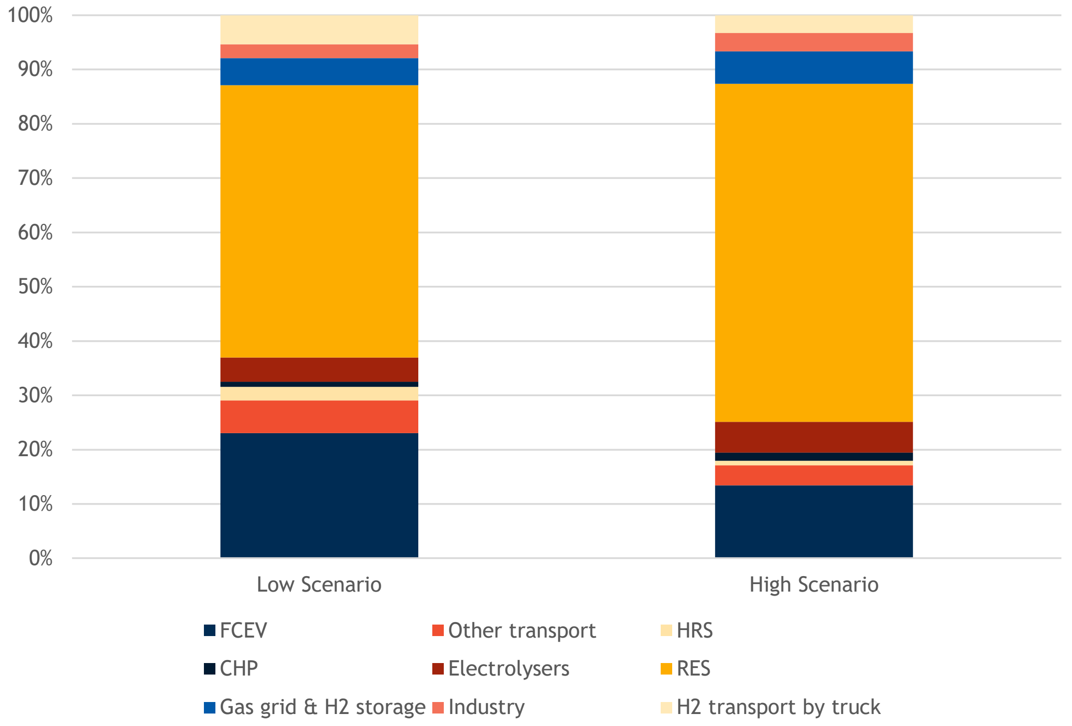


Figure 4-35 Employment Share per Value Chain Segment - EU28



5 Conclusions & recommendations

The analysis of the NECPs shows that EU Member States are increasingly considering hydrogen deployment as part of their strategy to decarbonise energy supply. In the final NECPs for 2021-2030, hydrogen is much more prevalent than in the draft NECPs submitted early 2019, showing that hydrogen is gaining momentum in the debate on decarbonising the EU economy. Several Member States refer in their NECP to the potential benefits and contributions of hydrogen to energy and climate goals and present their existing or intended generic or hydrogen-specific measures and initiatives. These initiatives mainly focus on research, pilot and demonstration projects for hydrogen production, transport/distribution and storage, and end-use, in particular for transport purposes. Several NECPs comprise expected or targeted hydrogen demand for 2030, while a few NECPs also include targets for hydrogen production.

As the NECPs are structured according to the sections defined in the Energy Governance Regulation (EU) 2018/1999, the information regarding policies and measures that are directly or indirectly related to hydrogen is not regrouped in one single section. Moreover, only some NECPs comprise concrete dedicated measures to facilitate hydrogen deployment and its integration into energy systems. Several Member States mention their intention to improve the regulatory framework for renewable gases, including hydrogen, and refer to financial or fiscal measures that would facilitate their development. However, the majority of NECPs do not address how the national regulatory frameworks will actually be improved and provide limited information regarding measures to effectively address the barriers to hydrogen deployment.

Several NECPs refer to specific hydrogen roadmaps or strategies that have been or will be elaborated at national level. These documents provide more comprehensive approaches, covering the different components of the hydrogen value chain. In most Member States, a specific hydrogen association or working group has been established; these are useful instruments for exchanging information and initiating and coordinating projects.

The opportunity assessment shows that most EU Member States have a technical potential for variable renewable electricity that (largely) exceeds their expected electricity demand in 2030. Building up additional renewable electricity generation capacity for hydrogen production using electrolysis would hence be technically possible in nearly all EU countries. This opportunity is reinforced by the increasing penetration of variable renewable electricity across the EU; the resulting increasing needs for system flexibility can be provided by power-to-hydrogen installations and by hydrogen-to-power. Several NECPs refer to this "driver" for hydrogen deployment, which shows that Member States are increasingly aware of this opportunity. In the two scenarios considered the installed electrolysis capacity would by 2030 reach 13 and 56 GW respectively to produce 42 and 183 TWh_{H2}/a respectively of renewable hydrogen.

The deployment of hydrogen facilitates optimised use of renewable energy resources, and allows further use of existing natural gas infrastructure, thereby avoiding stranded assets and reducing the investment needs for electricity transport and storage infrastructure. Moreover, it will offer a transition perspective for operators in the gas sector, allowing them to also deploy hydrogen activities, which is within their technical competences on handling gases. The IEA has also identified existing gas infrastructure as one of the key near-term opportunities to boost hydrogen.[87]

[87] IEA (2019). The Future of Hydrogen

The scenario assessment shows that hydrogen deployment offers substantial economic and environmental benefits. Domestic renewable hydrogen production will enable EU Member States to reduce their independence on (fossil) energy imports from outside the EU, thereby contributing to security of energy supply and energy independence. The scenario assessment in this study provides concrete figures to illustrate these main benefits. In the high scenario, the demand for renewable or low-carbon hydrogen would in 2030 reach 183 TWh (1.6% of total final energy demand in 2030 according to the EUCO3232.5 scenario[88]), that would be covered by 56 GW electrolyser capacity. Alternatively, in some countries with a high readiness for CO_2 storage (i.e. Germany, the Netherlands and the UK), low-carbon hydrogen can be produced via SMR + CCS. A SMR capacity of 9 GW_{H2} would be needed to cover the corresponding hydrogen demand in these countries (74 TWh_{H2}/a). Also according to the high scenario, domestic renewable hydrogen production would reduce fossil energy import independence by 1.5%, , generate an overall value added of 29 billion EUR annually, allow 67 Mt_{CO2}/a GHG emissions reduction, and create 106,980 direct and 250,650 indirect jobs.

The assessment also highlights that hydrogen and derived fuels can facilitate the decarbonisation in sectors and applications with limited abatement options, such as heavy-duty transport, high-temperature processes in industry, steel making, and the chemical and petrochemical sectors. Almost half of the renewable or low-carbon hydrogen volumes in 2030 are anticipated to be consumed in the industry, mainly by refineries and steelmaking, followed by the petrochemical industry and ammonia production for fertilizers. It will be important to take further steps in this direction in the coming years, in order to make sure that the switch to carbon-neutral or carbon-free fuels will speed up and carbon neutrality is reached by 2050. The scenario assessment shows that hydrogen deployment can contribute up to 20% in individual Member States to the gap towards the decarbonisation targets for 2030. In the international shipping and aviation sectors, hydrogen and derived fuels could also make a valuable contribution to decarbonisation, but given the specific technical challenges and the lack of a stimulating legal framework, these sectors do not yet assess and test hydrogen-based solutions at large scale and progress is thus limited. Therefore, it would be essential to also include these sectors in the core of the international climate change mitigation discussions and agree on targets for decarbonisation of these sectors that are in line with the Paris Agreement.

Notwithstanding the large technical potential for domestic hydrogen production, the effective deployment will, according to the NECPs, still be limited by 2030 for economic, technical and regulatory reasons. The economic viability of renewable hydrogen production is still an issue, but it is assumed that ongoing and planned research, pilot and industrial scale projects as well as market developments will substantially improve its competitiveness by 2030. The regulatory uncertainty is also referred to in several NECPs as a barrier. At national level, initiatives are being taken or announced to determine the threshold and technical specification for blending hydrogen with natural gas in the existing methane network. At EU level, the regulatory framework for dedicated hydrogen infrastructure and markets will be addressed by the European Commission in the context of the new gas regulatory package. Public acceptance of building energy infrastructure is in general an issue and leads to delays in the realisation of new projects. Using existing methane infrastructure as a basis for hydrogen transport and storage may mitigate this barrier and facilitate the deployment of dedicated hydrogen

[88] EUCO3232.5 scenario has been developed by the European Commission "to estimate the impact of the EU's climate and energy targets for 2030." It provides comprehensive scenario results on expected energy system layout by taking into account latest EU targets for GHG emission reduction, renewable energy targets (32%), and energy efficiency targets (32.5%) for all Member States. It is also officially used by the European Commission to evaluate the NECPs.
EC (2019). Technical Report on EUCO3232.5 Scenario. Available at https://ec.europa.eu/energy/en/data-analysis/energy-modelling/euco-scenarios

infrastructure; implementing power-to-hydrogen technologies will also reduce the need for investments in electricity infrastructure.

According to the NECPs, only a few Member States consider producing low-carbon hydrogen using SMR with CCS. A significant barrier for this technology is the slow development of CCS technologies. As hydrogen production by SMR using natural gas is at present the most competitive technology, combining it with CCS could act as a stepping stone to the development of dedicated hydrogen infrastructure, markets and end-user applications. However, only a few EU Member States have a high readiness for CCS development, and the lack of maturity of CCS technologies and appropriate transport and storage infrastructure constitutes a major barrier for this technology.

The NECPs provide a very useful overview of the different national energy and climate policies and measures and their contribution to the main policy objectives. However, with the current template imposed for the NECPs, hydrogen is addressed in different sections, and a consistent overview is hence not available in the NECPs. Taking into account that the deployment of renewable and low-carbon hydrogen is still in a preliminary phase, a specific comprehensive national hydrogen roadmap or strategy that considers the integration of hydrogen into a broader energy or industry policy framework could be an appropriate complementary document. A few Member States have meanwhile published such a national document, next to their NECP.

Such a national hydrogen roadmap or strategy could ideally comprise the following building blocks:

1. Assessment of the current situation, identifying existing barriers, main industrial and research actors, current initiatives and expertise on the national territory;
2. Identification of long-term expectations, potential developments and the role of hydrogen in the energy system, recognizing the versatility of hydrogen and how it can provide low carbon and competitive solutions to different sectors;
3. Definition of the short-term and long-term objectives as well as quantitative targets, planning the major milestones;
4. Setting up of the required institutional framework to ensure effective cooperation among the different stakeholders from all concerned sectors, including the decision makers;
5. Setting up of concrete policies and measures, and defining the resources needed. The policies and measures should ideally address each component of the value chain, including production, transport, storage and distribution infrastructure and the different end-use applications, and should cover research, pilots, deployment and market uptake.

As a whole, this study shows that hydrogen deployment can contribute to reaching the EU and national energy and climate objectives, in particular the binding target to reduce GHG emissions in the EU by at least 40% below 1990 levels by 2030. As the EU aims to achieve climate-neutrality (net zero GHG gas emissions) by 2050, and has the intention to raise the GHG emissions reduction target for 2030 to at least 50 to 55% from 1990 levels, most Member States might need to update their national decarbonisation strategies, in order to align them with this new target. This update may represent an opportunity for Member States to also review their hydrogen policies and targets for 2030 and to determine how to enable hydrogen deployment with the right set of policy measures. National teams working on these topics can use the information on opportunities and benefits of hydrogen deployment presented in this study as a reference.

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Annexes

Annex A - Detailed methodology, assumptions and sources

Methodology for the review of NECPs

Content review to identify relevant references to hydrogen

The NECPs and others relevant documents were reviewed in order to identify main references to hydrogen and PtX, potential sources of hydrogen, targeted use sectors, the role of hydrogen in the energy system and the political ambition to deploy hydrogen generation, delivery and end-use applications. The review also addresses any national hydrogen related objectives mentioned either in the NECP or in a hydrogen roadmap or strategy, such as overall hydrogen production/consumption or specific sectorial targets. The expected hydrogen consumption (where available in the NECP) is compared to the technical potential and the outcome of the two scenarios considered in our scenario assessment.

These observations have been summarised in the individual MS fiches developed in the context of this study. The national fiches comprise a high-level evaluation of the policy framework, addressing, where relevant and available, national political commitments towards hydrogen deployment, existing and announced measures and investments and major regulatory barriers.

Extraction of quantitative data for use in the assessments

The following NECP data were used in the assessments:

- Figures regarding expected hydrogen production and/or consumption in 2030;
- Data on variable renewable electricity generation and installed capacity in 2030, based on the With Additional Measures scenario;
- GHG reduction target in the non-ETS sectors and possible gap with the Effort Sharing Regulation target.

Assessment per EU Member State of opportunities for hydrogen deployment

Hydrogen production potential and its role in energy system flexibility

Production potentials for renewable and low-carbon hydrogen largely differ per Member State; the first are mainly dependent on the capacity to produce renewable electricity (it is assumed for our scenario assessment that dedicated renewable electricity generation capacity will be built that will be coupled with electrolysers for production of hydrogen), while the latter are dependent on the availability of fossil fuels and suitable sites for CO_2 storage or on the availability of electricity from nuclear power plants. The technical potential for renewable electricity generation is in the vast majority of EU Member States substantially larger than the expected national electricity demand in 2030; most Member States have hence a technical potential for building additional dedicated renewable electricity generation capacity for conversion into hydrogen using electrolysis.

The assessment also focuses on the potential role of power-to-hydrogen and hydrogen storage in providing energy system flexibility. The shift in most Member States to an electricity system largely based on variable renewable energy, leads to high fluctuations in electricity supply, causing challenges for balancing supply and demand. These increasing flexibility needs can be covered by hydrogen-based solutions (next to electricity storage, interconnection capacity, demand-response and dispatchable power generation). In times of high renewable electricity supply and low prices, electricity can be converted into hydrogen and can be directly used or stored for later use. While power-to-hydrogen can effectively contribute to decarbonising and balancing the electricity system, its economic feasibility depends on the investment cost and conversion efficiency, which are both expected to improve in the coming years, as well as on the electricity price and load factor, which should also improve with increasing availability of renewable electricity at low cost.

Low-carbon hydrogen can be produced from fossil fuels, combined with carbon capture, use or storage (CCUS). While the potential of CCU is not specifically considered in this study, the CCS potential is assessed on the basis of the country's availability of CO_2 storage capacity as well as its existing knowledge in that domain.

Gas transport, distribution and storage infrastructure

The national energy infrastructure is an important determinant for the deployment of hydrogen. In this context, the natural gas infrastructure is most relevant, as most of these assets can be used for transport or storage of hydrogen. According to Marcogaz, small hydrogen volumes (up to maximum 20 vol-%, depending on the type of end-use) can be injected into the methane grid without the need for adapting the network or end-use equipment.[89] This is an effective way to start decarbonising the gas supply. When the produced renewable or low-carbon hydrogen volumes will exceed a certain threshold, setting up a dedicated hydrogen network would be the preferred option. As transporting large energy volumes via hydrogen pipelines is ten times less expensive than via electricity cables, electrolysers and dedicated hydrogen networks may also be deployed to transport the output from large (renewable) power plants to end-users (industries, …). This requires investments in new pipelines or refurbishment of existing methane infrastructure, by adapting, amongst others, compressor stations, metering equipment and end-use appliances where necessary. Consequently, a parallel infrastructure of dedicated hydrogen pipelines and methane networks (transporting natural gas, biomethane, synthetic methane and possibly a limited share of hydrogen) may develop. In regions with high shares of hydrogen in their energy mix, dedicated cross-border transmission pipelines for hydrogen may also be realised.

The existence of suitable hydrogen storage infrastructure also represents an opportunity for hydrogen deployment, as it enables using hydrogen for short term or seasonal flexibility needs. Large-scale seasonal hydrogen storage would in particular represent an interesting opportunity for countries with a high heating demand in winter. Studies show that hydrogen storage is possible in salt caverns, and research is ongoing to investigate whether depleted gas fields could also be used for this purpose. In this study, the hydrogen storage potential per Member State is assessed based on existing natural gas storage sites in salt caverns and the presence of suitable salt formations that could be used for hydrogen storage.

Current and potential hydrogen demand

In this study, the national (potential) demand for hydrogen is assessed independently from the NECP data and from the national hydrogen production levels assumed for the scenario assessment, as hydrogen is expected to be produced where conditions are most favourable and to be traded across the EU via existing or refurbished/new gas infrastructure. A country with a low potential for renewable electricity-based hydrogen can hence rely on imports from neighbouring countries to cover its hydrogen

[89] Marcogaz (2019), Overview of available test results and regulatory limits for hydrogen admission into existing natural gas infrastructure and end-use appliances

demand. Furthermore, a global hydrogen market may develop, allowing to import renewable or low-carbon hydrogen from outside the EU. The demand opportunities in our analysis are hence based on the potential hydrogen use from a technical point of view, meaning that opportunities identified in our analysis do not necessarily match with policy priorities mentioned in NECPs.

Opportunities for hydrogen demand in industry: Hydrogen can contribute to decarbonising those parts of industrial processes that are hard to electrify. On the short term, the most promising application of renewable or low-carbon hydrogen is to replace existing use of fossil-derived hydrogen, which is at present typically produced from fossil fuels through steam reforming without CCUS and is used for the synthesis of chemicals (e.g. ammonia and methanol) or for hydro-cracking and desulphurization in oil refining processes.

A second role renewable and low-carbon hydrogen can play in industry is to replace fossil fuels for generation of (high-temperature) process heat or as feedstock. While electric heat pumps and boilers are suitable options for decarbonising low-temperature heat demand in industry, high-density energy carriers such as hydrogen are more suitable for generating high-temperature heat. Another particular use of hydrogen in industry is in primary steel production, where direct reduction of iron ore with hydrogen can replace coal-based blast furnace processes.

Opportunities for hydrogen demand in heating and cooling in the built environment: In the EU, about 30% of final energy demand is used for heating and cooling of buildings. In most countries this application still strongly depends on fossil fuels. While electric heat pumps provide a suitable and energy efficient solution for well insulated buildings, their application in the older building stock is challenging. Especially in regions where a large share of buildings is connected to a district heating grid or to a natural gas distribution grid, renewable or low-carbon hydrogen could contribute to decarbonising this energy use. Although still in their infancy, cooling technologies (e.g. air conditioners) using hydrogen as an energy source are under development and may become a suitable option in some Member States.

Opportunities for hydrogen demand in transport: The transport sector is one of the most fossil fuel-dependent sectors in the EU economy and decarbonising this energy use is challenging. While the overall greenhouse gas emissions in the EU declined by 22% between 1990 and 2017, the emissions from the transport sector increased over the same period by 28% and they are expected to further increase. Next to the use of renewable and low-carbon fuels including hydrogen, a shift to smarter and more integrated mobility is needed. Implementation of EU regulation will support this transition, in particular EU Directive 2014/94/EU on alternative fuels infrastructure and new CO_2 emission performance standards for passenger cars and heavy-duty vehicles.

In order to reach the required CO_2 emission reductions in the transport sector, a switch to renewable or low-carbon energy carriers is essential. Hydrogen can play a key role in this domain via its use in fuel cell-powered cars, trucks, buses, trains and ships. In road transport, fuel cell electric vehicles will, next to battery electric vehicles, be the main technologies to replace gasoline and diesel cars. Compared to battery electric vehicles, fuel cell vehicles have the advantage of a larger driving range and being able to be refuelled faster. In the shipping and aviation sectors, the use of hydrogen-based synthetic liquid fuels is a promising option. These synthetic fuels could also be used in cars or trucks with internal combustion engines, but the overall system energy efficiency of this route is rather low.

Enabling environment

National hydrogen policies and plans, projects and industry: A review was performed of national political, social and industrial factors in each MS as these significantly influence the national potential and opportunities for hydrogen development.

National hydrogen roadmap or strategy: The existence or not of a national hydrogen plan is a strong enabler for future energy applications of hydrogen. Any such roadmaps were identified and reviewed.

GHG mitigation gap in non-ETS sectors: EU Member States have committed to reducing their GHG emissions in non-ETS sectors following the 2030 targets defined in the Effort Sharing Regulation. Any remaining gaps to achieve these targets (as identified by the EC in its analysis of draft NECPs and recommendations[90]) could potentially be filled in by increasing hydrogen deployment.

The presence of a **dedicated national hydrogen association** will act as a driver of hydrogen development and is hence in this study considered as an enabler. Also, the existence of specific hydrogen related **assets or planned investments** (e.g. hydrogen refuelling stations or pilot electrolysers), or the allocation of **public RD&I** budgets to hydrogen related research are in this study considered as a strength or opportunity for hydrogen deployment. The implementation of the **Alternative Fuels Infrastructure Directive (2014/94/EU)** can in some Member States also represent an enabler hydrogen deployment, in particular if the national measures address hydrogen infrastructure.

Lastly, there are political and economic factors that indirectly stimulate local renewable or low-carbon hydrogen deployment, and can hence be considered as an opportunity for hydrogen deployment, such as **high energy import dependence** (the level of the import bill for natural gas) and the existence of **carbon pricing policies** (like a CO_2 pricing mechanisms in addition to the ETS) or carbon related vehicle taxation.

All these indicators can act as drivers of hydrogen development and were thus researched/ reviewed and assessed for all 28 MS. In some cases, information from the original sources (listed below) was updated based on bilateral feedback from Member State representatives.

[90] Published in DG ENER's website: https://ec.europa.eu/energy/en/topics/energy-strategy/national-energy-climate-plans

Indicator definitions and thresholds for opportunity identification

Table A-1 Indicator definitions and thresholds for opportunity identification

Indicator	Unit	Definition/explanation	Year	Sources	Assessment
Technical variable renewable electricity generation potential compared to 2030 electricity consumption	%	The sum of the technical potential for variable renewable electricity production in a country (wind energy and PV) compared to the 2030 final electricity consumption estimate in the NEPCP	2030	Trinomics, LBST & E3M (2019); Member State's NECP	High variable RES-E potential positively affects renewable H_2 production potential. There is an opportunity if technical potential for variable renewables > expected electricity demand in 2030
NECP variable renewable electricity generation compared to technical variable renewable electricity generation potential	%	Wind and solar power generation estimates (scenario with additional measures) mentioned in NECP, divided by technical variable renewable electricity generation potential	2030	Trinomics, LBST, E3M (2019); Member State's NECP	This value indicates how much of the technically feasible power generation capacity will be used for electricity consumption and whether there is a remaining potential to build up additional dedicated renewable electricity sources to produce hydrogen
Variable power generation capacity in 2030 compared to average load	%	Wind and solar capacity in the NECP compared to the average load from the EUCO scenario. (for members states which didn't include the figures on wind and solar installed capacity, the EUCO scenario figures are used)	2030	EC (2019 a); Member State's NECP	The variable power generation capacities (i.e. solar, wind) and their share in total load influence the potential to convert electricity into hydrogen. An opportunity for hydrogen arises if the variable power generation capacity is higher than the average load.
Variable renewable electricity production capacity compared to electricity interconnection capacity	%	Wind and solar capacity in the EUCO 3232.5 scenario compared to Net Transfer Capacity of interconnectors on bidding-zone borders in 2027 as estimated in ENTSO-E Ten-Year Network Development Plan 2018.	2030/2027	EC (2019 a); ENTSO-E TYNDP 2018	The existence of electricity cross-border interconnection capacity influences hydrogen development opportunities in different ways. It may be used to export or import surplus renewable electricity and thus affect opportunities for hydrogen production. It may be also used as flexibility provider for domestic system balancing and lower demand for other flexibility providers, including hydrogen-based solutions.
Readiness for CO_2 storage	Qualitative	The indicator assesses a country's geological storage potential, maturity of their storage assessments and progress in the deployment of CO_2 injection sites. The assessment is as follows: • **High**: Well-advanced countries which offer the potential for wide-scale CCS deployment because of available storage resources (though not always connected to infrastructure) and existing experience in storage operations relating to CCS. • **Low**: Limited readiness for wide-scale deployment of CCS. • **Very low**: No storage characterisation and limited understanding of storage potential.	2018	Global CCS Institute (2018)	Availability of suitable CO_2 storage capacity and related knowledge improves the potential to generate low-carbon hydrogen. There is hence an opportunity for hydrogen deployment if the country has suitable CO_2 storage sites and experience in storage operations (score = high).
Technical and economic feasibility of converting gas distribution networks to dedicated H_2	%	Provides an indication of the technical and economic feasibility of converting gas distribution networks to H_2. Defined as the share of polyethylene pipelines in the distribution system	2013	Marcogaz technical statistics	Pipelines made of polyethylene are better suited for conversion into H_2 than other types of pipes, and their conversion costs are hence lower. Thus, it is considered an opportunity if the share of polyethylene pipelines is above 50%.
Intensity of use of the gas distribution network [91]	GWh/km	Ratio of gas demand households and services and the total length of the gas distribution network (GWh/km). This indicator provides an indication of the intensity of use of the gas distribution network.	2016	CEER (2016)	The size of the existing gas networks indicates the potential for injection of (admixture of) H_2 or synthetic CH_4 into the gas grid; a large density and coverage is considered as an opportunity.

[91] A specific indicator on the number of connections to the TSO gas grid has not been included for two reasons. First, the gas demand from large companies connected to the TSO-grid is anyhow reflected in the indicator on the share of natural gas in the final energy mix in the industry, and second, the number of connections to the TSO grid can be misleading as the consumption level per connection differs greatly, which makes such an indicator difficult to compare across countries.

Indicator	Unit	Definition/explanation	Year	Sources	Assessment
Existing salt cavern natural gas storage sites	TWh	Existing, under construction and planned gas storage capacity in salt caverns in 2018 (TWh).	2018	GIE storage DB	Existing salt cavern storage capacity provides opportunities for seasonal or short-term storage of hydrogen. There is hence an opportunity if the country disposes of existing storage capacity in salt caverns.
Suitable geological formations (potential for future hydrogen storage sites)	Yes/No	Presence of underground salt layers that are potentially suitable for future hydrogen storage.	NA	Robinius, M. et al (2018)	The existence of suitable geological formations also provides opportunities for hydrogen storage.
Ammonia industry presence	%	Share of national ammonia production capacity in total production capacity EU28. The relative volume for production of ammonia allows to estimate the size of the potential market.	2016	Communication with fertilisers Europe	Presence of ammonia industry (>0%) implies there is/will be potential demand for renewable or low-carbon H_2 which is an opportunity.
Refining industry presence	%	Presence of refineries: share of captive hydrogen production in refineries in EU28	2016/2018	IHS Markit (2018): Hydrogen, H2tools Hydrogen Analysis Resource Center	Existence of refineries in the country (>0%) implies there is (grey) hydrogen use in the sector, which is an opportunity for hydrogen deployment.
Presence of primary steel production	%	Share of national capacity for primary steel production in total primary steel production capacity in the EU (2018 data).	2018	World Steel Association (2019)	Presence of primary steel industry (>0%) implies there will be potential demand for renewable or low-carbon H_2 which is an opportunity
Share of natural gas in industrial energy demand	%	Share of gas in final energy demand in industry in 2017	2017	ESTAT - Complete energy balances	The higher the share of gas in industrial energy demand, the higher the potential demand for hydrogen. A gas share > 25% is considered an opportunity.
Share of High-temperature (>200°C) process heat in industrial energy demand	%	This indicator is calculated as follows: (Energy demand for process heat 200-500°C + Energy demand for process heat >500°C)/ total final energy demand in industry	2015	Fraunhofer ISI (2016)	Opportunities relating to this indicator have been assessed together with the other indicators for industry in a qualitative manner.
Share of natural gas in the household and service sector energy demand	%	Share of gas in final energy demand in households and services 2017	2017	ESTAT - Complete energy balances	The higher the share of gas in residential & service energy demand, the higher the potential demand for hydrogen. A gas share > 25% is considered an opportunity
Share of heating in the household and service sector energy demand	%	Energy demand for space heating & hot water and in households and services and demand for process heat in services, as a share of the total final energy demand in households and services	2015	Fraunhofer ISI (2016)	In countries with a substantial share of natural gas demand in households and services, especially for heating and cooling, an opportunity rises to lower the carbon footprint by switching to hydrogen.
Share of cooling in the household and service sector energy demand	%	Energy demand for cooling in households and services, including space cooling as well as process cooling in the service sector as a share of the total final energy demand in households and services	2015	Fraunhofer ISI (2016)	In countries with a substantial share of natural gas demand in households and services, especially for heating and cooling, an opportunity rises to lower the carbon footprint by switching to hydrogen.
Share of heavy transport (trucks, buses & vans) in total energy demand in road transport in 2020	%	This indicator is calculated as follows: (Energy use Public road transport + Heavy goods and light commercial vehicles)/total energy demand road transport	2020	EUCO32325 scenario[92]	Opportunities relating to this indicator have been assessed together with the other indicators for transport in a qualitative manner.
Share of fossil fuels in energy use of rail transport	%	Share of fossil fuel use by trains in total final energy use by trains	2017	ESTAT - Complete energy balances	There is an opportunity if the share is higher than 10%.
Share of inland shipping in overall energy demand for transport	%	Share of fossil fuel use by inland shipping in total final energy use	2017	ESTAT - Complete energy balances	There is an opportunity if the share is higher than 1%
Energy use by international shipping relative to total (domestic) final energy use in transport	%	(maritime bunkering)/(total final energy demand transport+ energy demand maritime bunkering + energy demand international aviation)	2017	ESTAT - Complete energy balances	There is an opportunity if the share is higher than 5%

[92] Motor vehicle movements on national territory, by vehicles registration

Indicator	Unit	Definition/explanation	Year	Sources	Assessment
Share of aviation in overall energy demand for transport (incl. energy use int. aviation)	%	(final energy demand domestic aviation + international aviation)/(final energy demand in transport + energy demand international aviation + energy demand maritime bunkers)	2017	ESTAT - Complete energy balances	There is an opportunity if the share is higher than 5%
Share of fossil fuels in energy use of road transport	%	Share of fossil fuel use in road transport in the total final energy use road transport	2017	ESTAT - Complete energy balances	A high share (>90%) of fossil fuel is considered an opportunity.
Existence of national hydrogen roadmaps or strategies	Yes/No/ Limited	Existence of (or concrete plans for) hydrogen roadmaps and strategies in the NECPs	2018	NECP	The inclusion of strategies for hydrogen technologies deployment in the NECP contributes to an enabling environment.
GHG mitigation gap in non ETS sectors (need for additional GHG reduction measures)	Yes/No	In its review of draft NECPs, the EC recommended considering additional measures to achieve the non-ETS national GHG emission reduction targets	2019	EC recommendations on the Member State's NECP	Both renewable and low-carbon hydrogen can serve as an additional measure for extra mitigation.
Existence of (active) hydrogen national association	Yes/No	Country has a national hydrogen association which is member of Hydrogen Europe	2019	Hydrogen Europe (2019)	Existence of national hydrogen association contributes to an enabling environment.
Inclusion of hydrogen in national plans for the deployment of alternative fuels infrastructure (2014/94/EU)	Yes/No	This indicator shows whether hydrogen is included in the in national plans for alternative infrastructure in the framework of Directive 2014/94/EU	2017	SWD(2017) 365	Inclusion of hydrogen in the national Alternative Fuels Infrastructure Plans contributes to an enabling environment, as it shows the country's commitment to hydrogen in the transport sector
Existence of hydrogen refuelling stations (2019)	Number	Number of hydrogen refuelling stations in the country; The ratio of passenger cars per hydrogen refuelling stations	2019 2017[93]	LBST HRS database; Eurostat (2019 c). transport data	Current and expected density of hydrogen refuelling stations contributes to an enabling environment towards the introduction of hydrogen road vehicles.
RD&I annual expenditure on hydrogen & fuel cells	M EUR	Average annual expenditure on research and development on hydrogen and fuel cells between 2013-2017.	Average 2013-2017	IEA RD&I budget expenditures database	A substantial budget contributes to an enabling environment.
Number of power-to-gas projects (existing & planned)	Number	Number of power-to-gas projects which are in operation, planned or under construction.	2019	LBST Internal Database	Number of existing PtG projects indicates the potential for admixture of H_2 or synthetic CH_4 into the gas grid.
Existence of national CO_2 pricing mechanism	Yes/No/ Planned	This indicator assesses whether there are national CO_2 pricing mechanisms on top of the ETS price (e.g. price floor in some MSs) and for non-ETS sectors (national CO_2 taxes/levies)	2018	World Bank (2018)	Such national CO_2 pricing mechanisms could act as an additional driver of renewable or low-carbon hydrogen deployment, and thus contribute to an enabling environment.
Import bill for natural gas as share of national GVA	%	Net import of natural gas as share of the country's GVA in current prices	2017	ESTAT: Trade data	For countries with a high natural gas import dependence, hydrogen deployment can be a strategy for increasing security of supply and reducing energy dependence.
Import bill for all fossil fuels as share of national GVA	%	Net import of fossil fuels as share of the country's GVA in current prices	2017	ESTAT: Trade data	For countries with a high oil and petroleum import dependence hydrogen deployment can be a strategy for increasing security of supply and reducing energy dependence.

[93] 2017 for data on numbers of cars; 2019 for numbers of refuelling stations.

Scenario assessment per EU Member State of hydrogen deployment

The objective of the scenario assessment is to estimate the cost-effective potential of hydrogen, hydrogen technology deployment inducing additional renewable power generation to feed the electrolysis, infrastructure implications as well as the resulting environmental and economic impacts in the EU28 Member States.

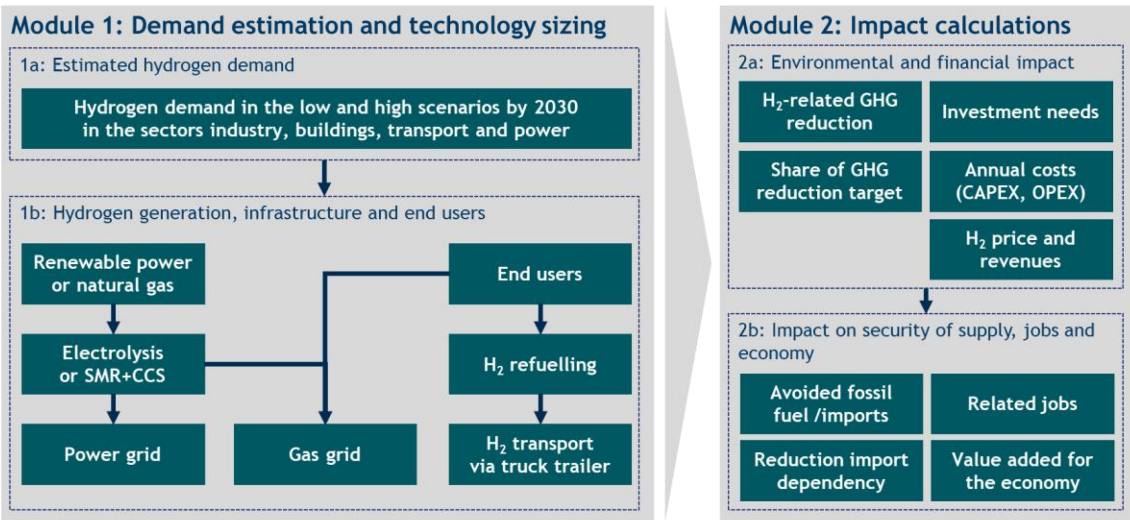
In order to cover for a range uncertainty **two scenarios** are defined with a **low and high share of hydrogen** technology in the relevant demand sectors. In the "Low" scenario a limited penetration of hydrogen in the different end-use applications is assumed. In the "High" scenario, it is assumed that the development of hydrogen will be strongly supported by increasing competitiveness of hydrogen technologies and by enabling policy measures.

The assessment takes into account both historical market size and expected market growth until 2030 for the following **demand sectors**:

- **Industry:** crude oil refining, production of steel and chemicals such as ammonia, methanol and olefins/aromatics as well as energy demand for industrial process heat;
- **Buildings:** energy demand for space heating and warm water[94];
- **Transport:** passenger cars, buses, trucks, trains, aviation (hydrogen-based liquids via Power-to-Liquids, PtL) and inland navigation (hydrogen-based liquids via PtL.

The analysis employs a proprietary input-output calculation model which can be subdivided into two major modules and related sub-modules (see Figure B-1). In the first step (Module 1), it is estimated that the hydrogen demand in different sectors and sub-sectors as a starting point of the analysis (Sub-module 1a) and use these results for the sizing of the corresponding hydrogen-related technologies for generation, infrastructures and end-users such as electrolysis, gas grids or end user applications (Sub-module 1b). In the second step (Module 2) we use the outcomes from the first module to assess the corresponding environmental and financial impact (Sub-module 2a) as well as the impact on security of energy supply, jobs and value added (Sub-module 2b) in each Member State.

Figure B-1 Structure of the input-output model employed in the scenario assessment



[94] Note that hydrogen-based cooling was not included in the assessment as it still has a relatively low TRL.

Hydrogen demand estimation (Sub-module 1a)

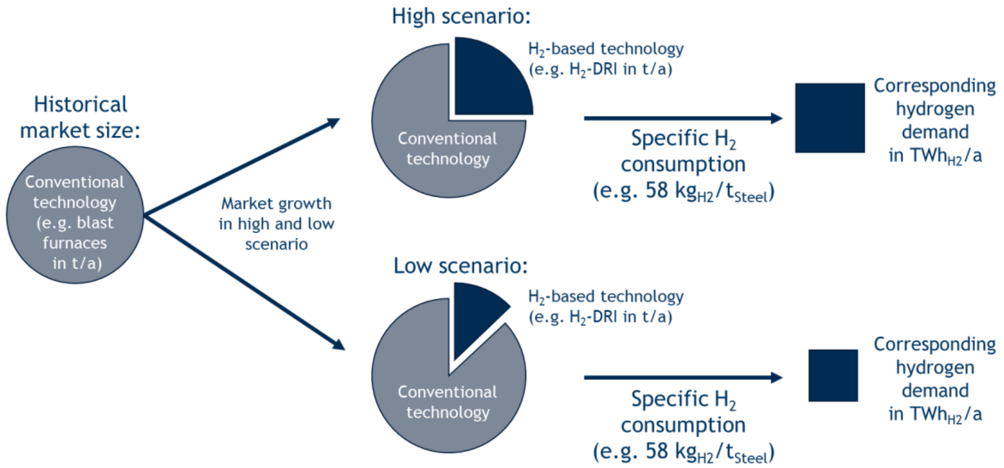
Based on the bottom-up approach the calculation model for the hydrogen demand in each Member State includes three major input parameter sets (see Figure B-2).

First, the size and volume indicators relate to the development of the overall demand in the respective sectors and sub-sectors such as production volumes (e.g. crude steel production in tonnes per year), vehicle usage (e.g. number of person-kilometres driven per year), or the annual energy consumption.

The second set of parameters is related to the technology split specifying the share of hydrogen technology in certain volume indicators. This corresponds to the penetration rate of hydrogen in the given market. These parameters are derived from techno-economic assessments in available literature for the EU as a whole for the timeframe until 2030 and generally considered as cost-effective on the basis of the literature sources. In case country-specific penetration rates are not be available, this estimation is based on a number of quantitative (e.g. number of hydrogen refuelling stations today), semi-quantitative (e.g. strategy/announcements for hydrogen refuelling stations build-up) and qualitative indicators (e.g. decision to build a hydrogen refuelling stations infrastructure according to AFID, membership in the government support group). Some sectors such as ammonia production or refining processes already use today conventional hydrogen from fossil fuels e.g. through steam methane reforming (SMR) or as a by-product from other chemical processes. In this case the penetration rate also corresponds to renewable hydrogen[95] or, in some selected countries with the corresponding potential (see Opportunity Assessment in Chapter 3), to low-carbon[96] hydrogen.

Finally, the actual hydrogen demand in each sector and sub-sector is calculated based on the previous results and technology specific energy consumptions and efficiencies. In this way the Sub-module provides annual demand for renewable (or in selected Member States low carbon) hydrogen in TWh_{H2}/a based on lower heating value. Both scenarios assume that in 2030 renewable or low-carbon hydrogen will be provided to partially substitute current conventional production and to cover additional demand (e.g. from the transport sector).

Figure B-2 Approach for estimation of hydrogen demand



[95] Renewable hydrogen corresponds to hydrogen produced via electrolysis based on fully renewable power generation such as wind or PV.
[96] Low-carbon hydrogen corresponds to hydrogen produced via steam methane reforming (SMR) combined with carbon capture and storage (CCS).

Hydrogen generation, infrastructures and end-users (Sub-module 1b)

The bottom-up approach of the hydrogen demand calculation provides input data for the assessment of the technology and infrastructure implications per Member State:

- **Renewable power:** dedicated renewable power supply for renewable hydrogen production via electrolysis in TWh/a is calculated by dividing respective hydrogen demand by the efficiency of electrolysis (69%) and multiplying with an oversizing factor (>100%, oversizing the renewable power feed-in to improve the utilisation of the electrolysis);
- **Natural gas:** methane demand for low-carbon hydrogen production in TWh/a via SMR+CCS by dividing respective hydrogen demand by the efficiency of the SMR technology (69%);
- **Electrolysis:** the installed electrical capacity of the electrolysis in MW_{el} is calculated by dividing the annual renewable energy supply in TWh_{el}/a by a country-specific number of full load hours. The country-specific full load hours are derived from historical feed-in profiles of photovoltaics (PV), wind onshore and wind offshore in the selected countries (according to the preselected country-specific technology split) and taking into account the oversizing factor;
- **SMR+CCS:** the installed capacity of the SMR technology in MW_{In} is calculated by dividing the respective methane demand by the number of full load hours assuming a constant production profile and a predefined utilisation rate (i.e. 8.760 multiplied by the utilisation rate in %);
- **Power grid:** corresponds to the amount of renewable electricity in TWh_{el}/a transported via the grid to electrolysers in TWh/a and is calculated by multiplying the annual renewable energy supply in TWh_{el}/a by country-specific share of electricity in the power grid in %. In this context, for PtL production for aviation and inland navigation we assume onsite H_2 production requiring respective transport of electricity as heat recovery from electrolysis can be used to improve the PtL production process. For all other applications electrolysis is located in close proximity to the major source of renewable power generation (e.g. wind onshore). In this case only the electricity from other renewable power plants (e.g. PV and wind offshore) which might have a different location than the major renewable power source has to be transported to the electrolyser;
- **End users:** the number of FCEVs is calculated by multiplying the historical figures by hydrogen penetration rate in the corresponding sub-sectors. For trains the number of hydrogen-based standard units is obtained from dividing the hydrogen demand in this sub-sector by a typical annual hydrogen consumption of one standard unit. The number of micro combined heat and power (CHP) units is calculated by multiplying the hydrogen demand in the building sector by a calibration factor derived from the literature. For large CHPs the number of units is derived from the expected hydrogen use in district heating divided by country-specific full load hours (obtained from synthetic heating profiles for each Member State) and the typical size of one unit. Sizing of the seasonal hydrogen storage in the power sector for re-electrification (expressed in TWh_{H2}/a) depends on the relative electricity storage needs, expected power demand and corresponding share of renewable power generation by 2030 as well as storage size ratio (in $kWh_{Capacity}/kWh_{Energy\_Stored}$). The sizing of the end users in the remaining sectors (in particular industry including ammonia, methanol, olefins and aromatics and steel production as well as PtL production for aviation and navigation) is expressed as the share of the corresponding market size and thus equals the hydrogen penetration rate;
- **H_2 refuelling stations:** the number of hydrogen refuelling stations is calculated by applying a specific formula depending on the total number of fuel cell electric vehicles (FCEVs) derived from the literature;

- **Gas grid:** the amount of hydrogen in TWh/a transported either in dedicated pipelines or injected into the existing methane grid depends directly on the hydrogen demand in the specific sectors. We assume that hydrogen for heating in buildings and industrial process heat will be injected into the methane network and be used as such in methane end-user appliances (admixture up to a certain technical threshold). For hydrogen use as feedstock in industry (steelmaking, refineries etc.) we assume dedicated pipelines from the electrolysers to the industrial plants. Hydrogen in the transport sector consumed by fuel cell vehicles (i.e. excluding PtL production for aviation and inland navigation) is transported via truck trailers to the refuelling station. For PtL production hydrogen is produced onsite and no further hydrogen transport is required for this sector;
- **H_2 transport via truck trailers:** the number of truck trailers is based on the respective hydrogen demand in the transport sector (except for PtL production) and on the typical capacity of a truck and average driving distance.

Environmental and financial impacts (Sub-module 2a)

Environmental and financial impacts are calculated based on the estimated hydrogen demand and expected size of the hydrogen technology along the entire value chain (i.e. hydrogen generation as well as corresponding infrastructures and end users) from Module 1 in the following way:

- **H_2-related GHG reduction:** greenhouse gas (GHG) emission reduction in Mt CO_2eq/a is calculated by estimating the fossil fuels replaced by hydrogen in each sector (e.g. substitution of gasoline consumption by passenger cars with internal combustion engine through renewable hydrogen used by FCEVs) and their respective greenhouse gas footprint;
- **Share of GHG reduction target:** comparing the above mentioned absolute GHG emission reductions to the 2030 reduction targets results in the contribution of hydrogen to achieving these targets expressed in %;
- **Investment needs:** the cumulative investments in all hydrogen technologies in B€ are calculated by multiplying the size of each element of the hydrogen value chain (from generation to end users) by the respective specific investment costs;
- **Annual costs:** annual costs of all hydrogen technologies along the entire value chain until 2030 in M€/a include capital expenditures (CAPEX) expressed as annuity based on the investments, expected discount rate and respective lifetime, operating expenses (OPEX) containing fixed costs (typically expressed on percentage-basis of the corresponding investments) and any variable costs;
- **H_2 price and revenue:** the specific hydrogen price in €/kg_{H2} is estimated according to a cost-based approach, i.e. it refers to the total annual costs of all hydrogen technologies divided by the total consumption of renewable (or for some selected Member States low-carbon) hydrogen. The revenues are typically calculated by multiplying the H_2 price by the respective total hydrogen consumption and therefore equal the annual costs.

Impacts on security of energy supply, employment and value added (Sub-module 2b)

Energy security in terms of security of supply is assessed quantitatively based on avoided fossil fuel consumption and imports in TWh/a which can be directly derived from the calculations on H_2-related GHG reduction. The corresponding reduction in import dependency in %-points is then computed by comparing the specific import dependencies, typically expressed on percentage-basis as the share of imported energy in total energy demand, between the cases with and without hydrogen consumption.

For the evaluation of impacts on employment and value added, a supply chain analysis[97] methodology is applied. It is based on the data and assumptions used for the other aspects of our scenario assessment, complemented by data from the study on hydrogen technologies value chains, issued by the FCH JU[98]. To fill in gaps in available data, additional desk research was undertaken.

The impacts of investments and operations in transport, storage and end-user appliances are estimated per Member State. As there is high uncertainty regarding the location of equipment manufacturing activities in the EU, it is assumed that all the value added and employment effects will materialize in the country, where the investments in end-use appliances take place. This approach does not capture all the differences between Member States, but it nevertheless covers the whole domestic value retained in the EU.

The future demand for hydrogen technologies in the EU will not be fully covered by EU production, but also partly by imports from non-EU countries. This part of the employment and value-added effects would thus not be retained in the EU economy. Since the study on hydrogen technologies value chains, commissioned by FCH JU[99], provides estimates for the share of technology imports in 2030, we used this information to estimate the EU domestic benefits[100].

Our analysis consists of the following steps:

1. Estimate of the operational and capital expenditures per Member State
    a. For OPEX it is assumed that the whole amount is spent domestically;
    b. For CAPEX the assumed share of domestic spending is based on the estimated future EU trade balance for the particular technology.
2. Analysis of the technology costs:
    a. Estimating the cost breakdown of subcomponents and technology production steps.
3. Estimating direct value added and employment effects:
    a. The WIOD Input-Output database[101] and socio-economic account tables are used as a basis.
4. Estimating indirect value added and employment effects:
    a. These effects are assumed to result from activities in other sectors of national economy, induced by increased demand for the particular technology.

The resulting figures represent the gross annual value added and job creation impact. They do not correspond to the net impacts on value added or employment, as hydrogen deployment will replace other activities in the economy.

[97] Jenniches, 2018: Assessing the regional economic impacts of renewable energy sources – A literature review. Available at https://doi.org/10.1016/j.rser.2018.05.008.
[98] E4tech, 2019: Study on Value Chain and Manufacturing Competitiveness Analysis for Hydrogen and Fuel Cells Technologies. Study commissioned by FCH JU. Available at: https://www.fch.europa.eu/page/FCH-value-chain
[99] E4tech, 2019: Study on Value Chain and Manufacturing Competitiveness Analysis for Hydrogen and Fuel Cells Technologies. Study commissioned by FCH JU. Available at: https://www.fch.europa.eu/page/FCH-value-chain
[100] For example, the FCH JU study estimates that European production value in fuel cell electric vehicles will cover 69% of the European demand. It is then assumed, that in every member state, only 69% of the investment in this technology can regarded as domestic and the employment and value added effects are calculated only from this share of investment.
[101] WIOD, 2016: The World Input-Output Database (WIOD) November 2016 Release. Available at http://www.wiod.org/release16.

These estimates on the potential relative size of the hydrogen sector in the national economy, and on the value added and employment that would be created in the two considered scenarios might help Member States in considering policy measures to capture these potential benefits.
When it comes to the boundaries between direct and indirect impacts, we followed the approach of the study on hydrogen technologies value chains, commissioned by FCH JU[102]. This means that we have excluded raw material and energy inputs costs from the OPEX in order to calculate the value added and employment. Operational costs related to additional power transmission from renewable energy plants without electrolysers to electrolysers located elsewhere, were also excluded from the value added and employment impacts. Since no capacity additions are assumed to be needed, this additional power transmission will not directly induce additional value added or employment.

General assumptions

In this study we focus on domestic hydrogen production (i.e. no hydrogen imports from outside the EU and no hydrogen transport between the Member States) from renewable power (renewable hydrogen) or from steam methane reforming (SMR) in combination with carbon capture and storage (CCS; low-carbon hydrogen). While the technology investment costs are the same within the EU, we distinguish country-specific operational costs, in particular energy prices, subject to availability of the respective data.

The data are derived from the available literature for the EU28 and depend on data availability and quality. In case adequate country-specific quantitative data is not available, indicators and qualitative data are used to estimate the expected national figures.

Assumptions for sectoral development of hydrogen demand (Sub-module 1a)

This chapter describes the assumptions and corresponding data sources related to the sectoral development of hydrogen demand. Major input parameters such as historical and expected market size (volume indicators), as well as penetration rates of hydrogen technologies are also provided in Annex E.

Refining processes

The overall gross and net hydrogen demand from refineries is calculated with a proprietary refinery model as described in Hinicio & LBST (2016)[103] as refining processes are complex and each refinery is a unique chemical plant where actual hydrogen demand strongly depends on the input and output products and the actual design of the plant. A major element of uncertainty is to differentiate between gross and net hydrogen demand. Gross demand is partly covered by internal hydrogen production, while the remaining net demand, which is relevant for this study, is in general covered by dedicated hydrogen production by steam methane reforming of natural gas within the refineries or in very close geographical proximity (so-called captive hydrogen production). The results are then checked for consistency with the historical data provided by IHS Markit (2018)[104].

[102] E4tech, 2019: Study on Value Chain and Manufacturing Competitiveness Analysis for Hydrogen and Fuel Cells Technologies. Study commissioned by FCH JU. Available at: https://www.fch.europa.eu/page/FCH-value-chain
[103] Hinicio & LBST (2016). Power-to-gas - Short term and long term opportunities to leverage synergies between the electricity and transport sectors through power-to-hydrogen, Brussels/Munich, February 2016. Available at http://www.lbst.de/download/2016/Hinicio-LBST_2016_PtH2-study_Fondation-Tuck.pdf
[104] IHS Markit (2018). Chemicals Handbook – Hydrogen, May 2018.

The values for net hydrogen demand used here are about 45% lower than the values of the Hydrogen Roadmap Europe[105], which are mainly based on internal refining models of McKinsey[106]. Therefore, our estimates used here may be considered conservative. Also, the estimated increase in hydrogen demand by refineries is somewhat higher in the Hydrogen Roadmap Europe based on increased desulphurization requirements.

In this context, the model assumes that there will be no substantial changes in refinery processes until 2030 and, hence, there will be a constant ratio based on historical values for crude oil input to refinery products and oil input to hydrogen demand. However, changes in refinery capacities based on fuel demand from the transport sector occur following the demand for conventional fuel from the transport sector. The share of electricity in transport reducing fuel demand comes from the EUCO 3232.5 scenario in EC (2019)[107] (see also Annex D). At this point it is also worth mentioning that a lower hydrogen demand from refining might occur in the high scenario due to a larger penetration of FCEVs and thus lower overall diesel and gasoline consumption.

We do not foresee any differentiation between EU Member States given the existence of EU-wide regulations in RED II and assume the following penetration rates of renewable or low-carbon hydrogen:

- in the low scenario only from increased refinery capacities based on additional fuel consumption of conventional vehicles due to increased mobility needs; and
- in the high scenario from the increase of refinery capacities (plus 10% of today's H_2 production).

Ammonia production

Ammonia production volumes in the EU Member States are available both from Eurostat[108] until 2018 and the US Geological Survey (USGS)[109] until 2016. Both sources provide data for many Member States, but not for all. Where Eurostat does not provide 2018 data, the most recent available data is used. 2013 production capacities in the EU Member States are available from CEPS (2014)[110]. More recent capacity data for all EU Member States except Croatia and Estonia have been provided by Fertilizer Europe[111], which have been assumed here to represent best available capacity data; for Croatia and Estonia, CEPS (2014) data have been assumed here. Eurostat and USGS production data are combined to provide a comprehensive data set. For countries where both Eurostat and the USGS provide production data, the higher of the two values is chosen. However, if that value is above the production capacity, the lower value is chosen. Where only one sources provides production data, this value is assumed; and where both sources provide no data or zero production, zero is assumed. At EU level, ISI et al. (2018)[112] estimate an increase of ammonia production by 3.3% by 2030 compared to 2015. This estimated increase level is applied here to the current production values per Member State.

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105 FCH JU (2019). Hydrogen Roadmap Europe: A sustainable pathway for the European Energy Transition, 2019.
106 Wilthaner, M. (McKinsey): Personal communication (E-Mail) to Altmann, M., Michalski, J. (LBST). 17 JAN 2020
107 EC (2019). Technical Report on EUCO3232.5 Scenario. Available at https://ec.europa.eu/energy/en/data-analysis/energy-modelling/euco-scenarios
108 Eurostat: http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=DS-066342&lang=en (extracted: 16 September 2019)
109 United States Geological Survey (USGS): Mineral Yearbook Nitrogen 2016
110 CEPS (2014): Energy Prices Study, Consolidated version
111 Personal communication
112 ISI et al. (2018): SET-NAV Navigating the Roadmap for Clean, Secure and Efficient Energy Innovation;

ICF, ISI (2019)[113] develop different scenarios for feedstock use for ethylene (and other olefins), ammonia and methanol production in EU28. For 2030, this results in a 4.4% hydrogen use in 2030 for these chemicals in the CleanGas scenario, while hydrogen input is zero in other scenarios. ISI et al. (2018)[114] conclude on 5% ammonia production from non-conventional hydrogen in 2030 in EU28 in the TRANS-IPT scenario. On the basis of these two studies, we assume 0% ammonia production from renewable or low-carbon hydrogen in 2030 in the low scenario, and 5% ammonia production from renewable or low-carbon hydrogen in 2030 in the high scenario in all ammonia producing Member States.

Methanol production

Methanol production volumes in the EU Member States are available from Eurostat[115] until 2018. Only Germany and the Netherlands have relevant methanol production; small quantities are produced in France, Belgium and Spain. Production data for all EU Member States are available until 2018 except for the Netherlands where the latest available production data are for 2016. Overall, the EU is a major methanol importer. Production capacity data for major production facilities are available from IHS[116]. Production and capacity data are consistent. At EU level, ISI et al. (2018)[117] estimate an increase of methanol production by 4.6% by 2030 compared to 2015. This increase by 2030 is applied here to the current production values per EU Member State.

ICF, ISI 2019[118] develop different scenarios for feedstock use for ethylene (and other olefins), ammonia and methanol production in EU28. For 2030, this results in a 4.4% hydrogen use in 2030 for these chemicals in the CleanGas scenario, while hydrogen input is zero in the other scenarios. ISI et al. 2018[119] conclude on 5% methanol production from non-conventional hydrogen in 2030 in EU28 in the TRANS-IPT scenario.

On the basis of these two studies, we assume for all methanol producing Member States except the Netherlands 0% methanol production from renewable or low-carbon hydrogen in 2030 in the low scenario, and 5% methanol production from renewable or low-carbon hydrogen in 2030 in the high scenario. In the Netherlands, one methanol production facility has started a project to install a 20 MW electrolyser to deliver renewable hydrogen for methanol production, according to an announcement by Nouryon[120]. This will replace methanol production based on steam methane reforming of natural gas and has been announced to be reducing greenhouse gas emissions by 27,000 tons per year. Methanol production based on renewable hydrogen will represent 2.4% of the total Dutch methanol capacity, which according to the above sources has close to full capacity utilization. For the Netherlands, we thus assume 2.4% methanol production from renewable or low-carbon hydrogen in 2030 in the low scenario, and 7.4% methanol production from renewable or low-carbon hydrogen in 2030 in the high scenario.

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113 ICF, ISI (2019): Industrial Innovation: Pathways to deep decarbonisation of Industry. Part 2: Scenario analysis and pathways to deep decarbonisation

114 ISI et al. (2018): SET-NAV Navigating the Roadmap for Clean, Secure and Efficient Energy Innovation

115 Eurostat: http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=DS-066342&lang=en (extracted: 16 September 2019)

116 IHS Markit: Global Methanol Monthly Supplement; 10 September 2018, Issue 281

117 ISI et al. (2018): SET-NAV Navigating the Roadmap for Clean, Secure and Efficient Energy Innovation;

118 ICF, ISI (2019): Industrial Innovation: Pathways to deep decarbonisation of Industry. Part 2: Scenario analysis and pathways to deep decarbonisation

119 ISI et al. (2018): SET-NAV Navigating the Roadmap for Clean, Secure and Efficient Energy Innovation

120 Nouryon (2019): https://www.nouryon.com/news-and-events/news-overview/2019/biomcn-to-produce-renewable-methanol-with-green-hydrogen/ (accessed: 5 February 2020)

Olefins and aromatics production

Olefins and aromatics production is a major element of petrochemistry. Olefins include ethylene, propylene, C4-streams (butylene etc.), while aromatics include benzene, toluene, and xylenes. Olefins production volumes in the EU Member States are available from Eurostat[121] until 2018 for ethylene, propylene, butylene as well as buta-1,3-diene and isoprene separately. Aromatics production volumes in the EU Member States are available from Eurostat[122] until 2018 for benzene, toluene as well as for o-, p- and m-xylene separately. Where data are not available for 2018, latest available data have been used. For Member States where data are not available at all, estimates have been made. For this purpose, available country data for each olefin and aromatics type have been subtracted from the total EU28 production volume of olefins/aromatics providing the remaining production to be allocated to the remaining Member States. This distribution has been made on the basis of refining capacities in each of these Member States as olefins/aromatics production is typically part of refining operations. This has led to a comprehensive data set for all Member States. At EU level, ISI et al. (2018)[123] estimate an increase of ethylene production by 8.5% by 2030 compared to 2015. This increase by 2030 is applied here to the current olefins/aromatics production values per Member State.

ICF, ISI 2019[124] develop different scenarios for feedstock use for ethylene (and other olefins), ammonia and methanol production in EU28. For 2030, this results in a 4.4% hydrogen use in 2030 for these chemicals in the CleanGas scenario, while hydrogen input is zero in other scenarios. ISI et al. 2018[125] conclude on 5% methanol and ammonia production from non-conventional hydrogen in 2030 in EU28 in the TRANS-IPT scenario, while there are no specific values for olefins or aromatics. On the basis of these two studies, we assume for all olefins and/or aromatics producing Member States 0% olefins/aromatics production from renewable or low-carbon hydrogen in 2030 in the low scenario, and 5% olefins/aromatics production from renewable or low-carbon hydrogen in 2030 in the high scenario.

Steel production

The data estimates for the steel industry are based on historical values for the relative market size and the split between conventional steelmaking and EAF (electric arc furnaces) per Member State as provided by Worldsteel (2019)[126]. We assume an increase in annual steel demand by 3% and an increase in EAF due to better use of scrap by 17% until 2030 in all Member States as predicted by ISI (2019)[127] and in the long-term strategy vision in EC (2018)[128]. The specific hydrogen demand is estimated at 57.5 kg_{H2}/t_{Steel} as an average value from IEA (2019)[129]. The market penetration for hydrogen-based production through H_2-DRI processes (i.e. hydrogen-based direct reduction iron process) is assumed as follows:

- in the high scenario: one blast furnace per company in 3 Member States (Germany, Austria, Sweden and Finland), 2% of estimated overall steel production in 2030 in the other Member States in Western EU and 1% in Eastern EU Member States; and

[121] Eurostat: Total production by PRODCOM list (NACE Rev. 2) - annual data [DS-066342] (extracted: 15 January 2020)
[122] Eurostat: Total production by PRODCOM list (NACE Rev. 2) - annual data [DS-066342] (extracted: 15 January 2020)
[123] ISI et al. (2018): SET-NAV Navigating the Roadmap for Clean, Secure and Efficient Energy Innovation;
[124] ICF, ISI (2019): Industrial Innovation: Pathways to deep decarbonisation of Industry. Part 2: Scenario analysis and pathways to deep decarbonisation
[125] ISI et al. (2018): SET-NAV Navigating the Roadmap for Clean, Secure and Efficient Energy Innovation
[126] Worldsteel (2019). Worldsteel in Figures 2019.Available at https://www.worldsteel.org/en/dam/jcr:96d7a585-e6b2-4d63-b943-4cd9ab621a91/World%2520Steel%2520in%2520Figures%25202019.pdf
[127] ISI (2019). Industrial Innovation: Pathways to deep decarbonisation of Industry. Part 2: Scenario analysis and pathways to deep decarbonisation
[128] EC (2018). A Clean Planet for all A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy.
[129] IEA (2019). The Future of Hydrogen Report prepared by the IEA for the G20, Japan Seizing today's opportunities.

- in the low scenario: 1/3 of H_2 demand of the high scenario for some “advanced” Member States; no renewable or low-carbon hydrogen for the other Member States.

Industry energy and buildings[130]

Hydrogen demand for process heat in the industry and buildings sector is based on the expected gas demand estimated by Mapping Heating & Cooling study as presented in ISI (2017)[131]. We assume mainly hydrogen blending into natural gas grids, although limited dedicated hydrogen networks might be possible too. The differentiation between the Member States is based on country-specific regulatory frameworks, experience with dedicated hydrogen networks and projects with hydrogen injection into the gas grid:

- in low scenario 0.75 vol.% for “First Movers” and 0.25 vol.% for “Later Adopters”; and
- in high scenario 7.5 vol.% for “First Movers” and 2.5 vol.% for “Later Adopters”.

Transport

Calculations on hydrogen demand from the transport sector are based on historical fossil fuel demand from the EUCO3232.5 scenarios provided in EC (2019)[132] assuming unchanged mobility behaviour. The increase in each sub-sector until 2030 is derived from changes in mobility needs per Member State from preliminary NECPs (where available) and the EUCO3232.5 scenario in EC (2019)[133] where NECP data was not available). On EU28 level this leads to the following changes in mobility demand per sector for both scenarios:

- Cars: +13%;
- Buses: +8%;
- Trucks: +29%;
- Inland navigation: +7%;
- Aviation: +18%.

However, the overall energy demand in the transport sector decreases as fuel cell technology allows for a more efficient use of energy.

The differentiation between “First Movers”, “Followers” and “Later Adopters” for road transport is mainly conducted in a qualitative way and takes into account National Policy Frameworks for alternative fuels infrastructure under AFID, air pollution in urban areas, low emission zone schemes, road tolls exemptions, Government Support Group (GSG) membership. For rail transport our estimates are mainly based on non-electrified railways and result from Shift2Rail (2019)[134]. Regarding fuel use in inland navigation and aviation we do not differentiate between the Member States. Moreover, since we assume consumption of synthetic ship and jet fuel for inland navigation and aviation based on Power-to-Liquids (PtL) technology no end-user technology changes are assumed for ships and planes.

[130] For Portugal the absolute figures are used from scenario “H2_BASE_Export-“ from the draft national strategy “EN-H2 ESTRATÉGIA NACIONAL PARA O HIDROGÉNIO”, May 2020.
[131] Mapping and analyses of the current and future (2020 - 2030) heating/cooling fuel deployment (fossil/renewables), 2017.
[132] EC (2019). Technical Report on EUCO3232.5 Scenario. Available at https://ec.europa.eu/energy/en/data-analysis/energy-modelling/euco-scenarios
[133] Ibid.
[134] Shift2Rail (2019). Study on the use of Fuel Cells and Hydrogen in the Railway Environment, 2019. Based on the Portuguese draft national strategy, Portugal is classified as “Follower”.

The market penetration rate of the hydrogen technologies in the transport sector in the low and high scenario is summarized in Table A-2, respectively. The assumptions are partly based on the results from FCH JU (2019)[135], E4Tech (2019)[136], EUCO 3232.5[137] and Shift2Rail (2019)[138] and partly on own expertise.

The resulting hydrogen demand in 2030 in the low scenario is almost double as high as in the business as usual scenario of the Hydrogen Roadmap Europe[139]. The qualitative difference between our approach and the Hydrogen Roadmap approach is that our low scenario assumes some regulatory and financial support to hydrogen beyond a "business as usual". On the other hand, the ambitious scenario of the Hydrogen Roadmap estimates a 35% higher demand than in our high scenario. In essence, our two scenarios are closer to each other, and are in between the Hydrogen Roadmap range.

Translating the vehicle numbers in the scenarios of the Value Chain study[140] into hydrogen demand assuming the same vehicle consumption levels as used here, the Value Chain medium scenario is lower than our low scenario, and the Value Chain high scenario is lower than our high scenario. The background for this is that the Value Chain study models manufacturing capacities for fuel cells and fuel cell vehicles in Europe, which we do not take as a limiting factor for vehicle deployment – FCEVs may be imported from other world regions.

Table A-2 Market penetration rate of the hydrogen technologies in the transport sector in the scenarios for 2030

Sub-sector	Low scenario			High scenario		
	"First Mover"	"Follower"	"Later Adopter"	"First Mover"	"Follower"	"Later Adopter"
Cars	1%	0.5%	0.25%	2%	1%	0.5%
Buses	1%	0.5%	0%	2%	1%	0.5%
Trucks	0.5%	0.25%	0%	1%	0.5%	0.25%
Rail	12%	3%	2%	36%	12%	8%
Inland navigation	0.2%			1.9%		
Aviation	0.2%			1.9%		

Power sector

In the power sector, hydrogen re-electrification only in Member States with wind & PV shares on total electricity demand of above 50% (Denmark, Spain, Greece and Ireland) [141] was assumed based on the results from the EUCO3232.5 scenario in EC (2019)[142]. In this context, in the low scenario no hydrogen re-electrification is assumed whereas in the high scenario 1% of expected power demand in the selected Member States comes from hydrogen re-electrification according to the methodology and results

[135] FCH JU (2019). Hydrogen Roadmap Europe: A sustainable pathway for the European Energy Transition, 2019.
[136] E4Tech (2019). Study on Value Chain and Manufacturing Competitiveness Analysis for Hydrogen and Fuel Cells Technologies, Findings Report, London, September 2019. Available at https://www.fch.europa.eu/sites/default/files/Findings%20Report%20v4.pdf
[137] EC (2019). Technical Report on EUCO3232.5 Scenario. Available at https://ec.europa.eu/energy/en/data-analysis/energy-modelling/euco-scenarios
[138] Shift2Rail (2019). Study on the use of Fuel Cells and Hydrogen in the Railway Environment, 2019.
[139] FCH JU (2019). Hydrogen Roadmap Europe: A sustainable pathway for the European Energy Transition, 2019.
[140] E4Tech (2019). Study on Value Chain and Manufacturing Competitiveness Analysis for Hydrogen and Fuel Cells Technologies, Findings Report, London, September 2019. Available at https://www.fch.europa.eu/sites/default/files/Findings%20Report%20v4.pdf
[141] In addition, Portugal is classified as a country with H_2 demand for re-electrification in the power sector for its close grid connection to Spain.
[142] EC (2019). Technical Report on EUCO3232.5 Scenario. Available at https://ec.europa.eu/energy/en/data-analysis/energy-modelling/euco-scenarios

presented in FCH JU (2019)[143]. Moreover, the power supply by natural gas fuelled CHPs is based on historical data from ISI (2017)[144] and takes into account the use of hydrogen injected into the natural gas grid as described for the buildings and industry sectors.

Assumptions on hydrogen production, infrastructure and end-users (Sub-module 1b)

Historical profiles related to feed-in of PV, wind onshore and offshore are taken from ENTSO-E (2020)[145] for the reference year 2015. Regarding the sizing factor for renewable power plants, a factor of 110% derived from LBST (2019)[146] was assumed. The technology split between the renewable power plants corresponds to the respective potential in each Member State expressed as a share of the overall renewable potential derived from Trinomics, LBST, Artelys and E3M (2018) [147] (see also Annex D). The required renewable power generation for clean hydrogen production is then compared to the 2030 target data from publicly available NECPs (see Annex D). The techno-economic assumptions on low-carbon hydrogen production via SMR+CCS are provided in Annex B. In this context, SMR+CCS facilities are operated at a utilisation rate of 95% or 8,322 full load hours. The SMR efficiency is assumed at 69% and the CO_2 capture rate at 90%. SMR+CCS technology is considered only in countries with a potential for CCS: Germany, the Netherlands and the UK. The historical number of road vehicles as a reference for calculating the number of FCEVs is taken from Eurostat (2020b)[148] (see Chapter 4.2) whereas the referenced development of micro CHPs is based on results in E4Tech (2019)[149].

Assumptions for environmental and financial assessment (Sub-module 2a)

The financial assessment is based on specific techno-economic assumptions such as investments, CAPEX, OPEX, efficiencies and lifetime which are provided in Annex B. According to Asset (2018)[150] the discount rate used for all Member States and technologies is 8.5%. The exchange factor for USD is 0.86 EUR/USD. The energy prices for 2030 based on data in ENTSO-E & ENTSOG (2018)[151] as well as the carbon price based on EC (2019)[152] are summarized in Table A-3.

Table A-3 Assumed energy and carbon prices in 2030

Item	Unit	Value	Source
Carbon price	€/tCO2	28.00	EC (2019)
Solid fuels price	€/MWh	12.74	ENTSO-E & ENTSOG (2018)
Oil price	€/MWh	63.17	ENTSO-E & ENTSOG (2018)
Natural gas price	€/MWh	24.84	ENTSO-E & ENTSOG (2018)

[143] FCH JU (2019). Hydrogen Roadmap Europe: A sustainable pathway for the European Energy Transition, 2019.
[144] ISI (2017). Mapping and analyses of the current and future (2020 - 2030) heating/cooling fuel deployment (fossil/renewables), 2017.
[145] ENTSO-E (2020). Transparency Platform, Available at https://transparency.entsoe.eu/
[146] LBST (2019). Wasserstoffstudie NRW, March 2019. Available at https://www.wirtschaft.nrw/sites/default/files/asset/document/bericht_wasserstoffstudie_nrw-2019-04-09_komp.pdf
[147] Trinomics, LBST, Artelys and E3M (2018). The role of Trans-European gas infrastructure in the light of the 2050 decarbonisation targets, Rotterdam, 2018. For Portugal, we assume a split of 66% PV (with a utilisation rate of 1,850 full load hours) and 34% wind onshore.
[148] Eurostat (2020b). Stock of vehicles by category and NUTS 2 regions [tran_r_vehst]
[149] E4Tech (2019). Study on Value Chain and Manufacturing Competitiveness Analysis for Hydrogen and Fuel Cells Technologies, Findings Report, London, September 2019. Available at https://www.fch.europa.eu/sites/default/files/Findings%20Report%20v4.pdf
[150] Asset (2018). Technology pathways in decarbonisation scenarios, July 2018.
[151] ENTSO-E & ENTSOG (2018). TYNDP 2018, Annex II Methodology -Scenario Report.
[152] EC (2019). Technical Report on EUCO3232.5 Scenario. Available at https://ec.europa.eu/energy/en/data-analysis/energy-modelling/euco-scenarios

The country-specific power price for additional power consumption by some technologies (e.g. by electric arc furnaces required to further process steel provided by H_2-DRI facilities) is taken from the Technical Report on EUCO3232.5 Scenario in EC (2019)[153] whereas the specific costs for power transport come from Eurostat (2020)[154] (see also Annex D).

Carbon footprint data for the reference energy carriers and industrial processes applied for the environmental assessment is summarized in Table A-4. The historical (1990 and 2015) and expected (2030) GHG emissions for the entire energy system come from the scenario results per Member State presented in the Technical Report on EUCO3232.5 Scenario in EC (2019)[155].

Table A-4 Carbon footprint data for the selected energy carriers and industrial processes

Energy carrier/industrial process	Unit	Value	Source
Natural gas	t_{CO2}/MWh	0.202	JRC (2013)[156]
Diesel	t_{CO2}/MWh	0.264	JRC (2013)
Gasoline	t_{CO2}/MWh	0.264	JRC (2013)
Jet fuel	t_{CO2}/MWh	0.265	Derived from UBA (2014)[157]
Ship fuel	t_{CO2}/MWh	0.554	Derived from JRC (2014)[158]
Steel production	t_{CO2}/t_{Steel}	1.900	Material Economics (2019)[159]
Olefins production	$t_{CO2}/t_{Olefins}$	0.760	Dechema (2017)[160]
Aromatics production	$t_{CO2}/t_{Aromatics}$	0.550	Dechema (2017)

Note that for the power sector it was assumed that power production through re-electrification of hydrogen and CHP plants substitutes conventional power generation by comparatively clean conventional natural gas-fired power plants as a conservative approach.

Assumptions on impacts on security of energy supply, employment and value added (Sub-module 2b)

The following assumptions and data are used for the scenario assessment on security of energy supply, employment and value added in Sub-module 2b (see Figure B-1).

Assumptions security of energy supply: avoided fossil fuel imports and reduction in energy import dependency

The reference figures for 2030 including the overall energy imports of solid fuels, natural gas and oil, which can be potentially substituted by hydrogen, as well as the reference import dependency are

[153] EC (2019). Technical Report on EUCO3232.5 Scenario. Available at https://ec.europa.eu/energy/en/data-analysis/energy-modelling/euco-scenarios
[154] Eurostat (2020). Electricity prices components for non-household consumers - annual data (from 2007 onwards), band IF, [nrg_pc_205_c], 2020.
[155] EC (2019). Technical Report on EUCO3232.5 Scenario. Available at https://ec.europa.eu/energy/en/data-analysis/energy-modelling/euco-scenarios
[156] JRC (2013). Well-to-Wheels analysis of future automotive fuels and powertrains in the European context, TANK-TO-WHEELS (TTW) Report, Version 4, Luxembourg 2013.
[157] UBA (2014). Germany National Inventory Report, 2014.
[158] JRC (2014). Well-to-Wheels analysis of future automotive fuels and powertrains in the European context, WELL-TO-TANK (WTT) Report. Luxembourg, 2014.
[159] Material Economics (2019). Industrial Transformation 2050 - Pathways to Net-Zero Emissions from EU Heavy Industry, 2019.
[160] Dechema (2017). Low carbon energy and feedstock for the European chemical industry. Frankfurt, June 2017. Available at https://dechema.de/dechema_media/Downloads/Positionspapiere/Technology_study_Low_carbon_energy_and_feedstock_for_the_European_chemical_industry.pdf

derived from scenario results per Member State presented in the Technical Report on EUCO3232.5 Scenario in EC (2019)[161].

The following conversion factors are used to calculate the substituted amount of the respective energy carriers (see Table A-5).

Table A-5 Conversion factors for imported energy carriers

Sector/Sub-sector	Substituted energy carrier	Unit	Value	Source
Methanol production	Natural gas	$GJ/t_{Methanol}$	36.9	Dechema (2017)[162]
Steel production	Solid fuels	GJ/t_{Steel}	18	IEA (2019)[163]
	Natural gas	GJ/t_{Steel}	1	IEA (2019)[164]
Olefins production	Oil	$GJ/t_{Olefins}$	16.5	Dechema (2017)
Aromatics production	Oil	$GJ/t_{Aromatics}$	7	Dechema (2017)
Transport (diesel/gasoline/PtL)	Oil	$GJ_{Oil}/GJ_{Product}$	1.1	Derived from CONCAWE (2017)[165]

In other sectors the conversion factor either equals 1 MWh/MWh as renewable or low-carbon hydrogen directly substitutes the same energy content (i.e. industry energy and buildings substituting natural gas) or it takes into account the efficiency of the conventional hydrogen production as it substitutes hydrogen generation from natural gas (refining processes and ammonia production). For the power sector, it was assumed that power production through re-electrification of hydrogen and CHP plants does not substitute any power imports and therefore does not change the import dependency as a conservative approach.

Assumptions and methodology used for assessing the impacts on employment and value added

For the evaluation of the impacts of hydrogen deployment on employment and value added, a supply chain analysis methodology is applied. It is based on the data and assumptions used for the other aspects of our scenario assessment, complemented by data from the study on hydrogen technologies value chains, issued by the FCH JU. To fill in gaps in available data, additional desk research was undertaken.

The impacts related to investments and operations in transport, storage and end-user appliances are estimated per Member State. As there is high uncertainty regarding the location of equipment manufacturing activities in the EU, it is assumed that all the value added and employment effects will

[161] EC (2019). Technical Report on EUCO3232.5 Scenario. Available at https://ec.europa.eu/energy/en/data-analysis/energy-modelling/euco-scenarios
[162] Dechema (2017). Low carbon energy and feedstock for the European chemical industry. Frankfurt, June 2017. Available at https://dechema.de/dechema_media/Downloads/Positionspapiere/Technology_study_Low_carbon_energy_and_feedstock_for_the_European_chemical_industry.pdf
[163] IEA (2019). IEA G20 Hydrogen report: Assumptions. Available at https://iea.blob.core.windows.net/assets/a02a0c80-77b2-462e-a9d5-1099e0e572ce/IEA-The-Future-of-Hydrogen-Assumptions-Annex.pdf
[164] IEA (2019). IEA G20 Hydrogen report: Assumptions. Available at https://iea.blob.core.windows.net/assets/a02a0c80-77b2-462e-a9d5-1099e0e572ce/IEA-The-Future-of-Hydrogen-Assumptions-Annex.pdf
[165] CONCAWE (2017). Estimating the marginal CO2 intensities of EU refinery products; Report no. 1/17, Prepared for the CONCAWE Refinery Management Group by its Refinery Technology Support Group; January 2017; Available at https://www.concawe.eu/wp-content/uploads/2017/04/Rpt_17-1-1.pdf

materialize in the country, where the equipment or appliances are installed. This approach does not capture all the differences between Member States, but it nevertheless covers the whole domestic value retained in the EU.

The estimated demand for hydrogen equipment in the EU will not be fully covered by production within the EU, but also partly by imports from non-EU countries. This part of the employment and value-added effects would thus not be retained in the EU economy. Since the study on hydrogen technologies value chains, commissioned by FCH JU[166], provides estimates for the share of technology imports in 2030, this information was used to estimate the EU domestic benefits[167].

Our analysis consists of the following steps:

1. Estimate of the operational and capital expenditures per Member State
    a. For OPEX it is assumed that the whole amount is spent domestically;
    b. For CAPEX the assumed share of domestic spending is based on the estimated future EU trade balance for the particular technology.
2. Analysis of the technology costs
    a. Estimating the cost breakdown of subcomponents and technology production steps (see Annex C).
3. Estimating direct value added and employment effects;
    a. The WIOD Input-Output database[168] and structural business statistics are used as a basis.
4. Estimating indirect value added and employment effects
    a. These effects are assumed to result from activities in other sectors of the national economy, induced by an increased demand for the particular technology.

The resulting figures represent the gross annual value added and job creation impact. They do not correspond to the net impacts, as hydrogen deployment will also replace other activities in the economy.

In order to distinguish between direct and indirect impacts, the approach of the study on hydrogen technologies value chains, commissioned by FCH JU[169], was followed. This means that raw material and energy inputs costs were excluded from the OPEX in order to calculate the value added and employment. Operational costs related to additional power transmission from renewable energy plants without electrolysers to electrolysers located elsewhere, were also excluded from the value added and employment impacts. Since no capacity additions are assumed to be needed, this additional power transmission will not directly induce additional value added or employment.

These estimates on the potential relative size of the hydrogen sector in the national economy, and on the value added and employment that would be created in the two considered scenarios might help Member States in considering policy measures to capture these potential benefits.

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166 E4tech (2019) Study on Value Chain and Manufacturing Competitiveness Analysis for Hydrogen and Fuel Cells Technologies.

167 For example, the FCH JU study estimates that European production value in fuel cell electric vehicles will cover 69% of the European demand. It is then assumed, that in every member state, only 69% of the investment in this technology can regarded as domestic and the employment and value added effects are calculated only from this share of investment.

168 WIOD (2016)

169 E4Tech (2019) Study on Value Chain and Manufacturing Competitiveness Analysis for Hydrogen and Fuel Cells Technologies.

Annex B - Hydrogen energy technologies information

This Annex provides an overview of the fundamental technical and financial data of hydrogen energy technologies for the 2021 and 2030 timeframes from renewable power generation to hydrogen end use as applied in the calculations for this study. General descriptions and more details on the technologies can be found in a variety of studies, e.g. the Hydrogen Roadmap Europe[170], or IEA (2019)[171], and in the sources referenced for each technology in the tables below. The focus for renewable here is on solar photovoltaics as well as onshore and offshore wind being the most widespread cheapest renewable power technologies in the market and showing the largest additional potential for deployment.

Table B-1 Renewable power generation

Renewable power generation				
Wind onshore	**Unit**	**2021**	**2030**	**Source**
Investment	€/kW	1,282	1,161	Asset (2018)[172]
Fixed O&M costs	€/kW	14	14	Asset (2018)
Variable costs	€/kWh	18	18	Asset (2018)
Lifetime	a	25	25	Asset (2018)
Wind offshore	**Unit**	**2021**	**2030**	**Source**
Investment	€/kW	2,705	2,048	Asset (2018)
Fixed O&M costs	€/kW	41	31	Asset (2018)
Variable costs	€/kWh	39	39	Asset (2018)
Lifetime	a	25	25	Asset (2018)
Photovoltaics	**Unit**	**2021**	**2030**	**Source**
Investment	€/kW	705	663	Asset (2018)
Fixed O&M costs	€/kW	12	11	Asset (2018)
Variable costs	€/kWh	0	0	Asset (2018)
Lifetime	a	25	25	Asset (2018)

Hydrogen supply covers production, storage, transport and vehicle refuelling stations. Hydrogen is produced from electrical energy through electrolysis or from natural gas using steam methane reforming with carbon capture and storage including CO2 pipeline transport to the geological storage site. Hydrogen transport by truck is used for smaller quantities, e.g. for the supply of hydrogen refuelling stations, or by gas networks for the supply of large quantities, e.g. to industrial users.

[170] FCH JU (2019). Hydrogen Roadmap Europe: A sustainable pathway for the European Energy Transition, 2019.
[171] IEA (2019). The Future of Hydrogen – Seizing today's opportunities, June 2019.
[172] Asset (2018). Technology pathways in decarbonisation scenarios, July 2018.

Table B-2 Hydrogen supply

Hydrogen supply				
Electrolysis	**Unit**	**2021**	**2030**	**Source**
Investment	€/kW	1,154	402	Asset (2018)[173]
Fixed O&M costs	€/kW	42	18	Asset (2018)
Lifetime	h	95,000	95,000	IEA (2019)[174]
Efficiency	%	64%	69%	IEA (2019)

SMR with CCS	Unit	2021	2030	Source
Investment	€/kW	1,040	1,005	Asset (2018)
Fixed O&M costs	€/kW	42	40	Asset (2018)
Lifetime	a	25	25	Trinomics & LBST (2018)[175]
Efficiency	%	69%	69%	IEA (2019)
Utilisation	%	95%	95%	IEA (2019)
CO_2 capture rate	%	90%	90%	IEA (2019)
Storage size	d	1	1	Own assumption

H_2 storage	Unit	2021	2030	Source
Investment	€/MWh	5,520	4,800	Asset (2018)
Fixed O&M costs	€/kW	0	0	Asset (2018)
Lifetime	a	30	30	Trinomics & LBST (2018)

H_2 truck trailer transport	Unit	2021	2030	Source
Variable costs	€/MWh	18.8	18.5	Asset (2018)

CO_2 transport	Unit	2021	2030	Source
Variable costs	€/t CO_2	4.4	4.4	Asset (2018)

CO_2 storage	Unit	2021	2030	Source
Variable costs	€/t CO_2	13.7	13.7	IPCC (2005)[176]

H_2 refuelling stations	Unit	2021	2030	Source
Investment	€	formula	formula	IEA (2019)
Fixed O&M costs	% of invest.	5%	5%	IEA (2019)
Lifetime	a	30	30	IEA (2019)

H_2 gas network	Unit	2021	2030	Source
Investment	€/kW	853	853	Asset (2018)[177]
CAPEX	€/kW	79	79	Asset (2018)
Fixed O&M costs	€/kW	34	34	Asset (2018)
Variable O&M costs	€/MWh	5	5	Asset (2018)
Lifetime	a	30	30	Trinomics & LBST (2018)[178]

[173] Asset (2018). Technology pathways in decarbonisation scenarios, July 2018.
[174] IEA (2019). IEA G20 Hydrogen report: Assumptions. Available at https://iea.blob.core.windows.net/assets/a02a0c80-77b2-462e-a9d5-1099e0e572ce/IEA-The-Future-of-Hydrogen-Assumptions-Annex.pdf
[175] Trinomics & LBST (2018). The role of Trans-European gas infrastructure in the light of the 2050 decarbonisation targets, Study for Dg ENER by Trinomics, LBST, Artelys and E3M, 2018.
[176] IPCC (2015). IPCC Special Report on Carbon Dioxide Capture and Storage, Cambridge, 2005. Available at https://www.ipcc.ch/report/carbon-dioxide-capture-and-storage/
[177] Asset (2018). Technology pathways in decarbonisation scenarios, July 2018.
[178] Trinomics & LBST (2018). The role of Trans-European gas infrastructure in the light of the 2050 decarbonisation targets, Study for Dg ENER by Trinomics, LBST, Artelys and E3M, Rotterdam, 2018.

Industrial end users of hydrogen listed in the table below are limited to innovative processes using hydrogen where the conventional processes are technically different and use fossil fuels such as coal in crude steel production in blast furnaces. Innovative crude steel making is based on direct reduction iron processes (H_2-DRI). Power-to-Liquids facilities produce liquid fuels from electrolytic hydrogen and CO_2. Methanol is produced from electrolytic hydrogen and CO_2.

Table B-3 End users: Industry

End users: Industry				
Steelmaking: H_2-DRI	**Unit**	**2021**	**2030**	**Source**
Investment	€/t_{Steel}	634	597	IEA (2019)
CAPEX	€/t_{Steel}	61.99	58.30	IEA (2019)
OPEX	€/t_{Steel}	89	98	IEA (2019)
Lifetime	a	25	25	IEA (2019)
Utilisation	%	95%	95%	IEA (2019)
Hydrogen consumption	kg_{H2}/t_{Steel}	57.5	57.5	IEA (2019)

PtL facility	Unit	2021	2030	Source
Investment	€/MWh_{PtL}	129	125	LBST & Hinicio (2019)[179]
CAPEX	€/MWh_{PtL}	12	12	LBST & Hinicio (2019)
OPEX	€/MWh_{PtL}	3	3	LBST & Hinicio (2019)
Lifetime	a	30	30	Fasihi et al. (2016)[180]

Methanol	Unit	2021	2030	Source
Investment	€/$t_{Methanol}$	93	88	Hinicio & LBST (2019)
CAPEX	€/$t_{Methanol}$	25	23	Hinicio & LBST (2019)
OPEX	€/$t_{Methanol}$	2	2.0	Hinicio & LBST (2019)
Lifetime	a	30	30	Fasihi et al. (2016)

Hydrogen use in transport includes passenger cars, trucks, buses, and trains. For this study it is assumed that marine transport and aviation rely on PtL fuels. For this study, vehicle costs are limited to the power train costs. The glider is excluded as it is assumed to be identical to conventional vehicles, and its inclusion in the cost calculations would provide misleading results.

[179] LBST & Hinicio (2019). Future Fuel for Road Freight Techno-Economic & Environmental Performance Comparison Of GHG-Neutral Fuels & Drivetrains For Heavy-Duty Trucks, Munich / Brussels / Paris, February 2019. Available at http://www.fondation-tuck.fr/upload/docs/application/pdf/2019-03/future-fuel-road-freight-report_lbst-hinicio_2019-02-19.pdf

[180] Fasihi et al. (2016). Techno-Economic Assessment of Power-to-Liquids (PtL) Fuels Production and Global Trading Based on Hybrid PV-Wind Power Plants; Energy Procedia 99 (2016) 243-268.

Table B-4 End users: Transport

End users: Transport				
Cars	**Unit**	**2021**	**2030**	**Source**
Investment	€/vehicle	9,400	7,000	E4Tech (2019)[181]
CAPEX	€/(vehicle*a)	1,178	877	E4Tech (2019)
Lifetime	a	13.9	13.9	LBST & dena (2017)[182]
Fuel cell size	kW_{net}/unit	80	80	E4Tech (2019)
Demand ratio (FCEV:ICE)	%	50%	41%	LBST & dena (2017)
Trucks	**Unit**	**2021**	**2030**	**Source**
Investment	€/vehicle	57,000	39,000	E4Tech (2019)
CAPEX	€/(vehicle*a)	10,108	6,916	E4Tech (2019)
Lifetime	a	8.0	8.0	LBST & dena (2017)
Fuel cell size	kW_{net}/unit	200	200	E4Tech (2019)
Demand ratio (FCEV:ICE)	%	70%	70%	LBST & dena (2017)
Buses	**Unit**	**2021**	**2030**	**Source**
Investment	€/vehicle	57,000	39,000	E4Tech (2019)
CAPEX	€/(vehicle*a)	7,775	5,320	E4Tech (2019)
Lifetime	a	12.0	12.0	LBST & dena (2017)
Fuel cell size	kW_net/unit	160	160	E4Tech (2019)
Demand ratio (FCEV:ICE)	%	67%	65%	LBST & dena (2017)
Trains	**Unit**	**2021**	**2030**	**Source**
Investment	€/vehicle	200,000	140,000	E4Tech (2019)[183]
CAPEX	€/(vehicle*a)	18,610	13,027	E4Tech (2019)
Lifetime	a	30.0	30.0	Shift2Rail (2019)[184]
Fuel cell size	kW_{net}/unit	300	300	E4Tech (2019)
Demand ratio (FCEV:ICE)	%	50%	50%	LBST & dena (2017)[185]

Hydrogen has a double role in the power sector: It can be produced from renewable energies when they are abundant, and can be stored and used for power generation when renewable power is short of demand (no wind, no sun). Also, hydrogen can be produced from dedicated renewable power plants, and used in CHP units of different sizes to provide power and heat to buildings or to industrial applications.

[181] E4Tech (2019). Study on Value Chain and Manufacturing Competitiveness Analysis for Hydrogen and Fuel Cells Technologies, Evidence Report, London, September 2019.
[182] LBST & dena (2017). E-Fuels – The potential of electricity-based fuels for low emission transport in the EU. Berlin, November 2017.
[183] E4Tech (2019). Study on Value Chain and Manufacturing Competitiveness Analysis for Hydrogen and Fuel Cells Technologies, Evidence Report, London, September 2019.
[184] Shift2Rail (2019). Study on the use of Fuel Cells and Hydrogen in the Railway Environment, 2019.
[185] LBST & dena (2017). E-Fuels – The potential of electricity-based fuels for low emission transport in the EU. Berlin, November 2017.

Table B-5 End users: Power generations

End users: Power generation				
Micro CHP	**Unit**	**2021**	**2030**	**Source**
Investment	€/unit	9,225	6,225	Roland Berger (2015)[186]
CAPEX	€/(unit*a)	1,111	750	Roland Berger (2015)
OPEX	€/(unit*a)	300	200	Roland Berger (2015)
Lifetime	a	15.0	15.0	Roland Berger (2015)
Fuel cell size	kW/unit	2.6	2.6	Roland Berger (2015)

Large CHP	Unit	2021	2030	Source
Investment	€/unit	1,166,400	221,298	Roland Berger (2015)
CAPEX	€/(unit*a)	177,768	33,728	Roland Berger (2015)
OPEX	€/(unit*a)	6,000	2,700	Roland Berger (2015)
Lifetime	a	10.0	10.0	Roland Berger (2015)
Fuel cell size	kW/unit	90.9	90.9	Roland Berger (2015)

Seasonal storage & H2 re-electrification	Unit	2021	2030	Source
Investment	€/kWh	0.25	0.25	LBST (2019)[187]
CAPEX	€/kWh	0.02	0.02	LBST (2019)
OPEX	€/kWh	0.005	0.005	LBST (2019)
OPEX	%	2%	2%	LBST (2019)
Lifetime gas turbine	a	30.0	30.0	LBST (2019)
Investment gas turbine	€/kW	400	400	LBST (2019)
Investment storage	€/kWh	0.86	0.86	LBST (2019)
Lifetime gas turbine	a	25	25	LBST (2019)
Lifetime H_2 storage	a	30	30	LBST (2019)
Storage-Output-Ratio	$kWh_{Storage}/kW_{el\ GT}$	500	500	LBST (2019)[188]
Gas turbine size	$kW/kWh_{Storage\ Size}$	0.0020	0.0020	LBST (2019)
Gas turbine size	kW/kWh_{Stored}	0.0003	0.0003	LBST (2019)
Storage Size Ratio	$kWh_{Storage}/kWh_{Stored}$	15%	15%	Michalski (2016)[189]
Storage Size	kWh/kWh_{Stored}	0.15	0.15	Michalski (2016)

[186] Roland Berger (2015). Advancing Europe's Energy System - Stationary fuel cells in distributed generation, March 2015. Available at https://www.rolandberger.com/de/Publications/Advancing-Europe's-Energy-System.html
[187] LBST (2019). Wasserstoffstudie NRW, March 2019. Available at https://www.wirtschaft.nrw/sites/default/files/asset/document/bericht_wasserstoffstudie_nrw-2019-04-09_komp.pdf
[188] LBST (2019). Wasserstoffstudie NRW, March 2019. Available at https://www.wirtschaft.nrw/sites/default/files/asset/document/bericht_wasserstoffstudie_nrw-2019-04-09_komp.pdf
[189] Michalski (2016). The Role of Energy Storage Technologies for the Integration of Renewable Electricity into the German Energy System, Munich, 2016. Available at https://mediatum.ub.tum.de/doc/1320110/1320110.pdf

Annex C - Assumptions for socio-economic assessment at sector level

Table C-1 Value added and employment multipliers for technologies included in FCH JU Value Chain study.[190]

	Value added intensity (EUR/EUR investment cost)[191]	Labour intensity (FTE/M EUR investment cost)[192]
Cars	0.250	1.72
Bus	0.200	1.36
Trucks	0.231	1.38
HGVs	0.231	1.38
Trains	0.176	1.18
HRS	0.375	4.79
Micro CHPs	0.219	2.78
Large CHPs	0.294	3.82
Electrolysis	0.333	2.92

Table C-2 Inputs for VA and employment calculations related to OPEX for technologies included in FCH JU Value Chain study.[193]

			OPEX cost breakdown					
	OPEX excluded	OPEX included	Maintenance	NACE sector	Land lease cost	NACE sector	Operations	NACE sector
Cars	x		OPEX excluded in the socio-economic impacts					
Bus	x							
Trucks	x							
HGVs	x							
Trains	x							
HRS		x						
Micro CHPs		x	55%	C33	Not applicable	45%	D35	
Large CHPs		x	45%	C33	18%	L68	37%	D35
Electrolysis		x	45%	C33	18%	L68	37%	D35

190 E4Tech (2019) Study on Value Chain and Manufacturing Competitiveness Analysis for Hydrogen and Fuel Cells Technologies.
191 This was calculated by dividing the total direct value added created per technology by the total production value (which are equivalent to investment costs in this study).
192 This was calculated by dividing the total direct employment in FTE per technology by the total production value (which are equivalent to investment costs in this study).
193 E4Tech (2019) Study on Value Chain and Manufacturing Competitiveness Analysis for Hydrogen and Fuel Cells Technologies.

Table C-3 Breakdowns of CAPEX and OPEX costs for renewable energy technologies, used as inputs for VA and employment calculations

	Onshore wind			Offshore wind			PV		
	Activity	NACE sector	Share (%)	Activity	NACE sector	Share (%)	Activity	NACE sector	Share (%)
CAPEX	Planning & miscellaneous	M71	6%	Planning & miscellaneous	M71	13%	Hardware	C27	75%
	Manufacture of WT towers	C25	17%	Wind turbines	C28	24%	Installation	C33	9%
	Manufacture of WT nacelles	C28	36%	Foundation	F	34%	Customer acquisition	M71	1%
	Manufacture of WT rotor blades	C22	22%	Development	M71	1%	Financing costs	K64	1%
	Foundation	F	4%	Connection to the grid	C27	11%	Margin		10%
	Development	M71	3%	Assembly of WPP	C33	11%	Permitting	N	0%
	Connection to the grid	C27	5%	Construction Finance	K64	6%	System design	M71	4%
	Assembly of WPP	C33	3%						
	Construction Finance	K64	4%						
OPEX	Maintenance	C33	55%	**Maintenance**	**C33**	**55%**	Maintenance	C33	45%
	Land **lease cost**	L68	16%	Land **lease cost**	L68	16%	Land **lease cost**	L68	18%
	Operations	D35	29%	Operations	D35	29%	Operations	D35	37%

Table C-4 Breakdowns of CAPEX and OPEX costs for hydrogen using industries, used as inputs for VA and employment calculations

	Steel production			Power-to-liquids			Methanol production		
	Activity	NACE sector	share (%)	Activity	NACE sector	share (%)	Activity	NACE sector	share (%)
CAPEX	Steelmaking machinery	C28	55%	CO2 liquefaction (compressors) and storage (tanks)	C28	16%	CO2 liquefaction (compressors) and storage (tanks)	C28	100%
	Construction	F	30%	FT plant		84%			
	Engineering & planning	M74&M75	10%	*Chemical installations*	C28	*67%*			
	Administration & permitting	N	5%	*Engineering & planning*	M71	*13%*			
				Administrative services (insurance etc)	N	*4%*			
source(s)	Voestalpine (2020)[194]			Hinicio & LBST (2019)[195]			Hinicio & LBST (2019)		
OPEX	Labour DRI operation*	C24	5%	Replacement of parts	C28	85%	Replacement of parts	C28	85%
	Replacement of machinery and parts	C28	95%	O&M labour	C20	10%	O&M labour	C20	10%
				Administrative services (insurance etc)	N	5%	Administrative services (insurance etc)	N	5%
source(s)				Hinicio & LBST (2019)			Hinicio & LBST (2019)		

** The share of labour costs in the OPEX for the operation of the steel plant were calculated by combining the labour intensity for DRI operation from literature[196], with the average labour costs in the steel sector from the WIOD I-O tables. Employment impacts in the steel sector was directly based on the labour intensity of DRI operation.*

[194] Voestalpine (2020) Personal communication.
[195] LBST & Hinicio (2019). Future Fuel for Road Freight Techno-Economic & Environmental Performance Comparison Of GHG-Neutral Fuels & Drivetrains For Heavy-Duty Trucks, Munich / Brussels / Paris, February 2019. Available at http://www.fondation-tuck.fr/upload/docs/application/pdf/2019-03/future-fuel-road-freight-report_lbst-hinicio_2019-02-19.pdf
[196] Steel Times International (2013) Iron ore and DRI – An old and new conference topic. https://www.steeltimesint.com/contentimages/features/iron_ore_joe_web_res.pdf

Table C-5 Breakdowns of CAPEX and OPEX costs for hydrogen storage and transport, used as inputs for VA and employment calculations

	Gas storage in tanks			Gas storage in salt caverns			hydrogen transport gas grid			hydrogen transport trucks		
	Activity	NACE sector	share (%)	Activity	NACE sector	share (%)	Activity	NACE sector	share (%)	Activity	NACE sector	share (%)
CAPEX				Brine disposal		**24%**	Machinery and equipment	C28	20%			
	Carbon fibre	C20	42%	*Disposal*	E37-E39	12%	Pipeline equipment	C24	55%			
	Resin		3%	*Storage*		1%	Other technical services	M71	10%			
	Wet winding	C28	5%	*Transportation*	H49	12%	Constructions /construction works	F	10%			
	Other tank		8%	Above ground		**26%**	Non-technical services	N	5%			
	Valve		7%	*Compressor*	C27	18%						
	Regulator	C27	11%	*Piping, Drying*	B	5%						
	Other BOP		24%	*Cushion Gas*	D35	4%						
				Underground		**49%**						
				Engineering & Permitting	M71	9%						
				Leaching	B	11%						
				Geological survey & Mechanical integrity test	M71	13%						
				Drill & Casing	C28	16%						
Source(s)	James, Houchins (2019)[197]			Ahluwalia et al (2019)[198]			Navigant (2019)[199]			N.A.		
Opex							Machinery and equipment	C28	29%	Freight transport by road	H49.4.1	100%
							Transport services	H49	14%			
							Administrative and support service activities	N	57%			
Source(s)							Navigant (2019)[200]					

[197] James, Houchins (2019). 2019 DOE Hydrogen and Fuel Cells Program Review: Hydrogen Storage Cost Analysis (ST100). Available at https://www.hydrogen.energy.gov/pdfs/review19/st100_james_2019_o.pdf

[198] Ahluwalia et al (2019). System Level Analysis of Hydrogen Storage Options. Available at https://www.hydrogen.energy.gov/pdfs/review19/st001_ahluwalia_2019_o.pdf

[199] Navigant (2019) Gas for Climate - Job creation by scaling up renewable gas in Europe.

[200] Ibid.

Annex D - Reference data for Scenario Assessment per Member State

Table D-1 Reference data for Scenario Assessment per Member State

		Overall renewable power potential			2030 renewable power target from NECPs		Power price	Power grid costs	Historical number of road vehicles			Share of electricity in transport
		Onshore	Offshore	PV	Wind	PV			Bus	Cars	Trucks	
		TWh/a	TWh/a	TWh/a	TWh/a	TWh/a	€/MWh	€/MWh	N°	N°	N°	%
Austria	**AT**	104.5	0.0	20.8	16.7	11.6	149.0	13.3	9,825	4,821,557	457,214	1.8%
Belgium	**BE**	15.5	4.0	17.9	5.6	9.7	160.0	8.8	16,040	5,712,061	842,679	2.4%
Bulgaria	**BG**	87.0	0.5	14.1			134.0	4.9	23,359	3,143,568	456,877	1.1%
Croatia	**HR**	41.5	6.7	8.6	3.5	1.0	133.0	10.6	5,513	1,552,904	156,673	1.8%
Cyprus	**CY**	4.0	0.0	1.9	1.3	0.3	189.0	7.0	2,842	508,284	106,304	1.3%
Czech	**CZ**	117.5	0.0	20.0	1.8	4.2	136.0	24.2	20,938	5,307,808	672,193	1.2%
Denmark	**DK**	152.0	56.5	9.4	38.4	6.3	206.0	13.0	13,417	2,465,538	438,967	2.2%
Estonia	**EE**	81.0	3.0	1.9	4.9	0.4	143.0	16.2	4,901	703,151	108,217	2.2%
Finland	**FI**	98.0	69.5	21.9	17.2	1.1	142.0	8.5	17,536	3,334,609	595,649	2.6%
France	**FR**	1,435.5	34.5	377.1			155.0	9.5	100,303	32,074,202	6,739,579	3.4%
Germany	**DE**	406.0	55.5	396.5			179.0	17.3	78,345	45,071,209	4,942,275	3.3%
Greece	**GR**	398.0	0.0	25.6	17.2	12.1	153.0	2.2	26,541	5,160,056	1,304,494	1.6%
Hungary	**HU**	145.0	0.0	21.9	0.7	6.6	156.0	15.6	18,482	3,313,206	517,078	1.3%
Ireland	**IE**	458.5	4.0	8.4			188.0	12.1	11,435	2,092,050	341,787	1.9%
Italy	**IT**	383.5	7.2	186.3	41.5	73.1	174.0	5.6	97,753	37,859,458	4,178,336	1.5%
Latvia	**LV**	164.5	40.0	2.8			128.0	9.8	4,641	664,177	84,067	2.2%
Lithuania	**LT**	251.0	6.5	4.1	0.4	0.1	158.0	16.3	7,326	1,298,737	109,396	1.1%
Luxembourg	**LU**	0.0	0.0	1.3			139.0	7.6	1,904	390,935	41,248	1.1%
Malta	**MT**	0.0	0.0	0.9		0.4	151.0	24.0	1,996	282,933	45,338	3.0%
Netherlands	**NL**	72.5	98.0	28.3	66.8	24.6	152.0	12.2	9,822	8,222,974	989,005	2.1%
Poland	**PL**	725.5	25.0	127.9	38.3	6.8	152.0	11.2	113,139	21,675,388	3,541,336	1.0%
Portugal	**PT**	67.5	0.0	27.4			156.0	13.3	14,850	4,850,229	73,106	1.8%
Romania	**RO**	286.0	14.0	68.5			123.0	15.4	48,803	5,472,423	912,790	1.4%
Slovakia	**SK**	46.5	0.0	8.7	1.0	1.3	141.0	17.0	9,091	2,121,774	309,290	1.4%
Slovenia	**SI**	4.0	0.0	3.9			118.0	8.8	2,679	1,096,523	96,892	2.6%
Spain	**ES**	1,389.5	1.0	255.3			168.0	4.4	61,838	22,876,830	5,087,369	2.1%
Sweden	**SE**	436.0	81.0	55.9			142.0	5.7	13,886	4,767,262	610,399	2.5%
UK	**UK**	959.0	314.0	141.2			178.0	22.4	165,317	31,163,706	4,464,712	3.4%

Annex E - Scenario assessment - Hydrogen demand related inputs and results

Table E-1 Historical market size (historical volume indicator)

		Industry feedstock						Ind. energy	Buildings	Transport						Power
		Historical	Historical	Historical	Historical	Historical	Historical	Historical	Historical	Historical	Historical	Historical	Historical	Historical	Historical	Historical
		Refinery	Ammonia	Methanol	Steel	Olefins	Aromatics	Ind. energy	Buldings	Bus	Cars	Trucks	Rail	Avaiiton	Navigation	Power
		TWh_{H2}/a	kt_{N}/a	$kt_{Methanol}$	Mt_{Steel}	$kt_{Olefins}$	$kt_{Aromatics}$	TWh_{CH4}/a	TWh_{CH4}/a	ktoe/a	ktoe/a	ktoe/a	ktoe/a	ktoe/a	ktoe/a	TWh/a
Austria	**AT**	1	400	0	7	379	0			103	4,708	2,622	41	776	23	
Belgium	**BE**	2	860	4	8	4,499	602			290	4,757	3,397	48	1,389	164	
Bulgaria	**BG**	1	313	0	1	105	0			263	1,628	646	16	207	49	
Croatia	**HR**	0	375	0	0	0	18			63	1,324	465	18	134	39	
Cyprus	**CY**	0	0	0	0	0	0			37	490	125	0	263	0	
Czech	**CZ**	2	180	0	5	370	312			385	3,319	1,914	86	345	4	
Denmark	**DK**	0	0	0	0	0	0			204	2,599	971	81	960	158	
Estonia	**EE**	0	163	0	0	0	0			74	524	132	19	42	6	
Finland	**FI**	3	78	0	4	339	90			121	2,631	1,145	23	746	159	
France	**FR**	6	1,045	14	15	5,047	840			654	31,615	9,543	141	6,827	499	
Germany	**DE**	14	2,727	1,130	42	10,849	2,712			815	35,814	11,780	319	9,601	285	
Greece	**GR**	5	119	0	2	0	0			403	4,018	1,480	41	936	612	
Hungary	**HU**	1	340	0	2	1,064	645			346	2,035	1,214	42	207	4	
Ireland	**IE**	0	0	0	0	0	0			111	2,583	1,019	36	809	21	
Italy	**IT**	11	570	0	25	2,451	752			1,278	24,747	8,259	22	4,073	1,012	
Latvia	**LV**	0	0	0	0	0	0			65	613	255	66	132	6	
Lithuania	**LT**	0	782	0	0	0	0			41	881	517	51	69	6	
Luxembourg	**LU**	0	0	0	2	0	0			115	1,311	818	5	435	3	
Malta	**MT**	0	0	0	0	0	0			12	109	31	0	105	0	
Netherlands	**NL**	10	2,300	477	7	5,345	1,462			267	7,708	2,594	32	3,821	239	
Poland	**PL**	5	2,200	0	10	834	561			632	10,120	6,957	84	613	3	
Portugal	**PT**	3	112	0	2	354	254			129	4,730	797	10	1,124	37	
Romania	**RO**	2	507	0	4	275	46			373	3,381	1,142	113	265	42	
Slovakia	**SK**	1	468	0	5	5	130			141	1,155	814	0	44	10	
Slovenia	**SI**	0	0	0	1	0	0			94	1,319	370	12	28	0	
Spain	**ES**	12	404	1	14	2,123	772			1,329	18,098	8,122	88	6,005	707	
Sweden	**SE**	5	0	0	5	580	0			187	4,890	1,921	2	945	85	
UK	**UK**	4	800	0	7	1,428	124			511	27,657	9,457	597	12,400	881	

Table E-2 Estimated market size by 2030 (volume indicator)

		Industry feedstock							Ind. energy	Buildings	Transport						Power
		2030	2030	2030	2030	2030	2030	2030	2030	2030	2030	2030	2030	2030	2030	2030	Historical
		Refinery (low)	Refinery (high)	Ammonia	Methanol	Steel	Olefins	Aromatics	Ind. energy	Buldings	Bus	Cars	Trucks	Rail	Aviaiton	Navigation	Power
		TWh_{H2}/a	TWh_{H2}/a	kt_N/a	$kt_{Methanol}$	Mt_{Steel}	$kt_{Olefins}$	$kt_{Aromatics}$	TWh_{CH4}/a	TWh_{CH4}/a	ktoe/a	ktoe/a	ktoe/a	ktoe/a	ktoe/a	ktoe/a	TWh/a
Austria	**AT**	1	1	413	0	7	411	0	22	26	108	5,392	3,499	50	833	27	79
Belgium	**BE**	2	2	889	5	8	4,882	653	40	52	290	5,408	4,626	73	1,548	210	71
Bulgaria	**BG**	2	2	323	0	1	114	0	7	6	180	2,083	1,628	15	348	68	47
Croatia	**HR**	0	0	388	0	0	0	19	4	4	67	1,435	623	29	160	47	14
Cyprus	**CY**	0	0	0	0	0	0	0	0	0	37	572	125	0	388	0	5
Czech	**CZ**	2	2	186	0	5	402	338	21	32	513	3,701	2,004	109	442	5	85
Denmark	**DK**	0	0	0	0	0	0	0	8	6	233	3,159	1,262	107	1,016	186	36
Estonia	**EE**	0	0	168	0	0	0	0	1	1	111	572	132	23	65	7	9
Finland	**FI**	3	3	81	0	4	368	97	7	4	121	2,747	1,349	28	760	178	94
France	**FR**	7	7	1,080	14	16	5,477	911	79	224	785	34,665	13,022	210	8,055	621	616
Germany	**DE**	15	15	2,817	1,182	44	11,775	2,943	188	333	786	37,903	15,439	397	9,425	350	606
Greece	**GR**	6	6	123	0	2	0	0	7	7	353	4,946	2,189	63	1,151	650	52
Hungary	**HU**	2	2	351	0	2	1,155	700	7	35	939	2,525	1,478	60	361	5	39
Ireland	**IE**	0	0	0	0	0	0	0	8	12	111	3,481	1,575	36	952	24	32
Italy	**IT**	12	12	589	0	25	2,660	816	94	297	1,356	26,526	9,883	32	4,326	1,196	301
Latvia	**LV**	0	0	0	0	0	0	0	3	3	55	755	301	34	172	8	7
Lithuania	**LT**	1	1	808	0	0	0	0	3	3	41	985	603	62	78	7	14
Luxembourg	**LU**	0	0	0	0	2	0	0	2	5	115	1,873	1,091	5	519	3	4
Malta	**MT**	0	0	0	0	0	0	0	0	0	12	109	31	0	133	0	2
Netherlands	**NL**	11	11	2,377	499	7	5,800	1,587	52	99	308	9,876	3,084	43	3,569	291	134
Poland	**PL**	7	7	2,273	0	10	905	608	54	57	704	13,115	9,554	147	883	5	196
Portugal	**PT**	3	3	116	0	2	384	276	11	7	151	5,335	956	16	1,360	43	47
Romania	**RO**	3	3	524	0	4	298	50	29	26	422	4,595	1,854	172	424	56	76
Slovakia	**SK**	1	1	484	0	5	5	141	8	24	188	1,733	1,047	0	71	13	39
Slovenia	**SI**	0	0	0	0	1	0	0	4	2	94	1,514	601	23	41	0	18
Spain	**ES**	14	14	417	1	15	2,304	838	86	65	1,424	21,372	10,100	106	6,961	865	286
Sweden	**SE**	6	6	0	0	5	630	0	9	6	229	5,319	2,255	3	1,078	115	189
UK	**UK**	4	4	827	0	7	1,549	135	71	300	544	31,350	10,519	736	11,929	1,001	396

Table E-3 Market penetration rate of hydrogen technologies in the respective sectors and sub-sectors in the low scenario

		Low scenario														
		Industry feedstock						Ind. energy	Buildings	Transport						Power
		2030	2030	2030	2030	2030	2030	2030	2030	2030	2030	2030	2030	2030	2030	2030
		Refinery	Ammonia	Methanol	Steel	Olefins	Aromatics	Ind. energy	Buldings	Bus	Cars	Trucks	Rail	Aviaiton	Navigation	Power
Austria	**AT**	14%	0%	0%	6%	0.0%	0.0%	0.75%	0.75%	1%	1%	1%	12%	0.2%	0.2%	0%
Belgium	**BE**	15%	0%	0%	0%	0.0%	0.0%	0.75%	0.75%	1%	1%	1%	3%	0.2%	0.2%	0%
Bulgaria	**BG**	34%	0%	0%	0%	0.0%	0.0%	0.25%	0.25%	1%	1%	0%	2%	0.2%	0.2%	0%
Croatia	**HR**	12%	0%	0%	0%	0.0%	0.0%	0.25%	0.25%	1%	1%	0%	2%	0.2%	0.2%	0%
Cyprus	**CY**	0%	0%	0%	0%	0.0%	0.0%	0.25%	0.25%	0%	0%	0%	2%	0.2%	0.2%	0%
Czech	**CZ**	9%	0%	0%	0%	0.0%	0.0%	0.25%	0.25%	1%	1%	1%	2%	0.2%	0.2%	0%
Denmark	**DK**	14%	0%	0%	0%	0.0%	0.0%	0.75%	0.75%	1%	1%	1%	12%	0.2%	0.2%	0%
Estonia	**EE**	0%	0%	0%	0%	0.0%	0.0%	0.25%	0.25%	0%	0%	0%	2%	0.2%	0.2%	0%
Finland	**FI**	5%	0%	0%	13%	0.0%	0.0%	0.75%	0.75%	0%	1%	0%	3%	0.2%	0.2%	0%
France	**FR**	11%	0%	0%	0%	0.0%	0.0%	0.75%	0.75%	1%	1%	1%	12%	0.2%	0.2%	0%
Germany	**DE**	5%	0%	0%	4%	0.0%	0.0%	0.75%	0.75%	1%	1%	1%	12%	0.2%	0.2%	0%
Greece	**GR**	19%	0%	0%	0%	0.0%	0.0%	0.25%	0.25%	1%	1%	0%	2%	0.2%	0.2%	0%
Hungary	**HU**	27%	0%	0%	0%	0.0%	0.0%	0.25%	0.25%	1%	1%	1%	2%	0.2%	0.2%	0%
Ireland	**IE**	25%	0%	0%	0%	0.0%	0.0%	0.25%	0.25%	0%	0%	0%	2%	0.2%	0.2%	0%
Italy	**IT**	7%	0%	0%	0%	0.0%	0.0%	0.75%	0.75%	1%	1%	1%	3%	0.2%	0.2%	0%
Latvia	**LV**	0%	0%	0%	0%	0.0%	0.0%	0.25%	0.25%	1%	1%	0%	3%	0.2%	0.2%	0%
Lithuania	**LT**	11%	0%	0%	0%	0.0%	0.0%	0.75%	0.75%	0%	0%	0%	3%	0.2%	0.2%	0%
Luxembourg	**LU**	0%	0%	0%	0%	0.0%	0.0%	0.25%	0.25%	1%	1%	0%	2%	0.2%	0.2%	0%
Malta	**MT**	0%	0%	0%	0%	0.0%	0.0%	0.25%	0.25%	0%	0%	0%	2%	0.2%	0.2%	0%
Netherlands	**NL**	13%	0%	2%	0%	0.0%	0.0%	0.75%	0.75%	1%	1%	1%	12%	0.2%	0.2%	0%
Poland	**PL**	24%	0%	0%	0%	0.0%	0.0%	0.25%	0.25%	1%	0%	0%	3%	0.2%	0.2%	0%
Portugal	**PT**	11%	0%	0%	0%	0.0%	0.0%	0.75%	0.75%	1%	1%	1%	3%	0.2%	0.2%	0%
Romania	**RO**	28%	0%	0%	0%	0.0%	0.0%	0.25%	0.25%	0%	0%	0%	2%	0.2%	0.2%	0%
Slovakia	**SK**	28%	0%	0%	0%	0.0%	0.0%	0.25%	0.25%	0%	0%	0%	2%	0.2%	0.2%	0%
Slovenia	**SI**	0%	0%	0%	0%	0.0%	0.0%	0.25%	0.25%	1%	1%	0%	2%	0.2%	0.2%	0%
Spain	**ES**	14%	0%	0%	0%	0.0%	0.0%	0.75%	0.75%	1%	1%	1%	3%	0.2%	0.2%	0%
Sweden	**SE**	8%	0%	0%	8%	0.0%	0.0%	0.75%	0.75%	1%	1%	1%	12%	0.2%	0.2%	0%
UK	**UK**	5%	0%	0%	0%	0.0%	0.0%	0.75%	0.75%	1%	1%	1%	12%	0.2%	0.2%	0%

Table E-4 Market penetration rate of hydrogen technologies in the respective sectors and sub-sectors in the high scenario

		High scenario														
		Industry feedstock						Ind. energy	Buildings	Transport						Power
		2030	2030	2030	2030	2030	2030	2030	2030	2030	2030	2030	2030	2030	2030	2030
		Refinery	Ammonia	Methanol	Steel	Olefins	Aromatics	Ind. energy	Buldings	Bus	Cars	Trucks	Rail	Aviaiton	Navigation	Power
Austria	**AT**	22%	5%	0%	18%	1.5%	1.5%	7.50%	7.50%	2%	2%	1%	36%	1.9%	1.9%	0%
Belgium	**BE**	23%	5%	5%	2%	1.5%	1.5%	7.50%	7.50%	2%	2%	1%	12%	1.9%	1.9%	0%
Bulgaria	**BG**	40%	5%	0%	0%	1.5%	1.5%	2.50%	2.50%	1%	1%	1%	8%	1.9%	1.9%	0%
Croatia	**HR**	20%	5%	0%	0%	1.5%	1.5%	2.50%	2.50%	1%	1%	1%	8%	1.9%	1.9%	0%
Cyprus	**CY**	0%	0%	0%	0%	1.5%	1.5%	2.50%	2.50%	1%	1%	0%	8%	1.9%	1.9%	0%
Czech	**CZ**	18%	5%	0%	1%	1.5%	1.5%	2.50%	2.50%	4%	1%	1%	8%	1.9%	1.9%	0%
Denmark	**DK**	22%	0%	0%	0%	1.5%	1.5%	7.50%	7.50%	2%	2%	1%	36%	1.9%	1.9%	1%
Estonia	**EE**	0%	5%	0%	0%	1.5%	1.5%	2.50%	2.50%	1%	1%	0%	8%	1.9%	1.9%	0%
Finland	**FI**	14%	5%	0%	40%	1.5%	1.5%	7.50%	7.50%	1%	1%	0%	12%	1.9%	1.9%	0%
France	**FR**	19%	5%	5%	2%	1.5%	1.5%	7.50%	7.50%	2%	2%	1%	36%	1.9%	1.9%	0%
Germany	**DE**	14%	5%	5%	13%	1.5%	1.5%	7.50%	7.50%	2%	2%	1%	36%	1.9%	1.9%	0%
Greece	**GR**	26%	5%	0%	0%	1.5%	1.5%	2.50%	2.50%	1%	1%	1%	8%	1.9%	1.9%	1%
Hungary	**HU**	34%	5%	0%	1%	1.5%	1.5%	2.50%	2.50%	2%	2%	1%	8%	1.9%	1.9%	0%
Ireland	**IE**	32%	0%	0%	0%	1.5%	1.5%	2.50%	2.50%	1%	1%	0%	8%	1.9%	1.9%	1%
Italy	**IT**	16%	5%	0%	2%	1.5%	1.5%	7.50%	7.50%	2%	2%	1%	12%	1.9%	1.9%	0%
Latvia	**LV**	0%	0%	0%	0%	1.5%	1.5%	2.50%	2.50%	1%	1%	1%	12%	1.9%	1.9%	0%
Lithuania	**LT**	19%	5%	0%	0%	1.5%	1.5%	7.50%	7.50%	1%	1%	0%	12%	1.9%	1.9%	0%
Luxembourg	**LU**	0%	0%	0%	0%	1.5%	1.5%	2.50%	2.50%	1%	1%	1%	8%	1.9%	1.9%	0%
Malta	**MT**	0%	0%	0%	0%	1.5%	1.5%	2.50%	2.50%	1%	1%	0%	8%	1.9%	1.9%	0%
Netherlands	**NL**	20%	5%	7%	2%	1.5%	1.5%	7.50%	7.50%	2%	2%	1%	36%	1.9%	1.9%	0%
Poland	**PL**	31%	5%	0%	1%	1.5%	1.5%	2.50%	2.50%	1%	1%	1%	12%	1.9%	1.9%	0%
Portugal	**PT**	19%	5%	0%	0%	1.5%	1.5%	68.00%	68.00%	2%	2%	1%	12%	1.9%	1.9%	1%
Romania	**RO**	35%	5%	0%	1%	1.5%	1.5%	2.50%	2.50%	1%	1%	0%	8%	1.9%	1.9%	0%
Slovakia	**SK**	35%	5%	0%	1%	1.5%	1.5%	2.50%	2.50%	1%	1%	0%	8%	1.9%	1.9%	0%
Slovenia	**SI**	0%	0%	0%	0%	1.5%	1.5%	2.50%	2.50%	1%	1%	1%	8%	1.9%	1.9%	0%
Spain	**ES**	22%	5%	5%	2%	1.5%	1.5%	7.50%	7.50%	2%	2%	1%	12%	1.9%	1.9%	1%
Sweden	**SE**	16%	0%	0%	25%	1.5%	1.5%	7.50%	7.50%	2%	2%	1%	36%	1.9%	1.9%	0%
UK	**UK**	13%	5%	0%	2%	1.5%	1.5%	7.50%	7.50%	2%	2%	1%	36%	1.9%	1.9%	0%

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